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REPORT DRXTH-TE-CR-83212

# THERMAL PROCESS DEVELOPMENT

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APRIL 8, 1983

PHASE I FINAL TECHNICAL REPORT FOR THE PERIOD 5 MAY 1982 TO 31 MARCH 1983

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Prepared for:

U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY
ABERDEEN PROVING GROUND, MARYLAND 21010

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| BLISTER AGENTS | MOLTEN SALT REACTOR | SHAFT FURNACE | |
| FLUIDIZED BED | NERVE AGENTS | THERMAL DESTRUCTION | |
| INCINERATION | PYROLYSIS | UNDERGROUND DETONATION | |

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

THE PURPOSE OF THIS STUDY WAS TO IDENTIFY THERMAL DESTRUCTION CONCEPTS APPLICABLE TO THE DISPOSAL OF CHEMICAL AGENT MUNITIONS. FOURTY-FOUR PROCESS CONCEPTS WERE IDENTIFIED AND EIGHT SELECTED AS BEING MOST VIABLE. THESE EIGHT CONCEPTS WERE EVALUATED IN DETAIL FROM BOTH A TECHNICAL AND ECONOMIC STANDPOINT. A DESIGN PLAN FOR THE FURTHER DEVELOPMENT OF FOUR OF THE CONCEPTS WAS PREPARED.

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April 8, 1983

Commander
U.S. Army Toxic and Hazardous
Materials Agency
Attn: DRXTH-TE-D/Lt. Ronald Fournier
Building E-4585
Aberdeen Proving Ground
Edgewood Area, Maryland 21010

Dear Lt. Fournier:

Thermal Process Development
Contract No. DAAK11-82-C-0055
Final Report
BCL Project No. G8027

Enclosed are ten copies of Battelle's Final Phase I Report (Data Item A002 of the subject contract) on your Thermal Process Development program. This report incorporates your comments of March 9, 1983.

Very truly yours,

William H. Mink

William H. Mink
Program Manager
Hazardous Materials
Program Office
Energy and Chemical
Processes Department

/pvh

DRXTH-TE-D (10 copies)
DRXTH-ESD (16 copies)

cc: DRDAR-PRB-R (letter only)

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APPENDIX L



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## LIST OF FIGURES
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SUMMARY

Experience with the Chemical Agent Munitions Disposal System (CAMDS) prototype suggested the need for development of thermal destruction technology to support the design of larger scale disposal facilities. These larger scale facilities will be required to demilitarize existing chemical agent stockpiles. As a first step in this further development, this Thermal Process Development program was undertaken by Battelle for the Army.

The program began with a study of literature and industrial information on thermal destruction concepts which were at various stages of development. The concepts were evaluated by a team of engineers knowledgeable in the area of thermal processing. This was done by developing criteria and rating each of 44 process concepts identified. By this means, eight processes were identified as having promise for the thermal destruction portion of a chemical agent munitions disposal facility. These eight processes were then evaluated in depth to identify the most viable. The eight processes are listed in Table 1 in general order of engineering and economic preference together with a summary of the information developed during the analysis.

Four processes (Acid Roaster, Rotary Kiln, Molten Metal, and Fluidized Bed) were selected as having the greatest potential for success. It is recommended that these four processes be evaluated in detail in laboratory and pilot scale studies.

TABLE 1. SUMMARY OF THERMAL PROCESS ENGINEERING AND ECONOMIC EVALUATION
(Processes Listed in General Order of Engineering and Economic Preference)

| Process | Applicable Feed Configuration | Life Cycle Costs $MM: Single Site 100 lb/hr | Single Site 400 lb/hr | Single Site 1000 lb/hr | Collocated 1000 lb/hr | Collocated 3000 lb/hr | Collocated 5000 lb/hr | Remarks |
|---|---|---|---|---|---|---|---|---|
| Acid Roaster | 1. Separate whole munitions | 23.6 | 21.0 | 31.1 | 87.2 | 104.6 | 134.3 | Minimum front-end preparation; low technical risk; probably lowest total facility cost |
| Rotary Kiln | 1. Munitions with agent cavity opened and energetic material removed and cut | 62.7 | 36.0 | 30.2 | 66.4 | 38.4 | 36.1 | Minimum technical risk; Simple system; high reuse potential; state-of-the-art technology; potential for "fast-track" |
| | 2. Shredded munition | 17.8 | 12.8 | 13.2 | 29.9 | 27.3 | 30.4 | |
| Molten Metal | 1. Munitions with agent cavity opened and energetic material removed and cut, or shredded munitions | 18.9 | 15.0 | 18.6 | 37.4 | 40.9 | 48.7 | Moderate technical risk; near state-of-the-art technology; optimum ultimate disposal and metal parts handling; high thermal inertia; low manpower requirements |
| Fluidized Bed | 1. Munitions with agent cavity opened and energetic material removed and cut | 20.2 | 17.6 | [illegible].7 | 39.2 | 32.3 | 35.1 | Moderate technical risk; near state-of-the-art technology; high thermal inertia; more complex than molten metal |
| | 2. Shredded munitions | 18.6 | 16.2 | 18.6 | 36.4 | 31.8 | 34.6 | |
| IR Vacuum Removal | 1. Whole munition, punctured and fuses removed | 23.5 | 17.1 | 18.9 | 36.4 | 35.5 | 41.0 | High technical risk; low thermal inertia |
| Shaft Furnace | 1. Cut or punched rockets, ton containers, bombs and spray tank, otherwise whole munitions | 34.1 | 31.9 | 50.5 | 100.0 | 158.6 | 215.0 | Very high technical risk |
| Molten Salt | 1. Shredded munitions | 22.8 | 18.4 | 22.4 | 45.4 | 59.7 | 77.9 | High degree of front end preparation required; moderate risk; no advantages not inherent in molten metal |
| Underground Detonation | 1. Stored munitions (loaded pallets) | -- | -- | -- | ← | 393 | → | Very high cost; high technical risk |

DRAFT FINAL REPORT

Contract No. DAAK11-82-C-0055

on

THERMAL PROCESS DEVELOPMENT

to

U.S. ARMY
TOXIC & HAZARDOUS MATERIALS AGENCY
Edgewood, Maryland

from

BATTELLE
Columbus Laboratories

by

W. H. Mink, H. E. Carlton, D. W. Folsom
D. R. Hopper, J. J. McNeely, and A. E. Weller

January 28, 1983

## 1.0 INTRODUCTION

As a result of environmental constraints and legislation, the methods used for disposing of military lethal agents such as GB, VX, and HD, have changed from land and sea burial to chemical neutralization and incineration. To study these processes, the Army developed a Chemical Agent Munitions Disposal (CAMDS) facility at the Army Depot at Tooele, Utah. This is a prototype for other lethal chemical demilitarization plants expected to be built in the future.

The CAMDS facility has provided much valuable information on chemical agent munitions disposal. It has been possible through its operation to identify several problem areas. For the chemical neutralization processes used with the nerve agents, these are:

- The chemical neutralization reaction is relatively slow, so that large reactors are needed to achieve reasonable throughput.
- The waste products are soluble, strongly alkaline, and toxic materials. The neutralization process consumes reagents. There is some chance of regeneration of agent from the neutralization products--at least for GB.
- The process is labor- and energy-intensive.

The specific incineration process selected for destroying the mustards at CAMDS was chosen in large part for its simplicity in handling the agent. However, simplicity in that area imposes significant disadvantages for the overall process. These disadvantages are:

- The process requires substantially more capital equipment than a more straightforward incineration process.
- The thermal parts of the process are complex and require complex controls.
- The process is energy-intensive and requires substantial fuel inputs to destroy an agent which itself has a fairly high fuel value.

Viewed as a total, CAMDS is a collection of independent processes with minimal interfaces, representing the available/demonstrated technology.

In view of these deficiencies and disadvantages, the Army initiated a program to determine whether new technology or new combinations of technology could form the basis for the next generation of chemical agent demilitarization plants with improved characteristics. To this objective, three RFQ's were issued: one on mechanical processes (munition disassembly/downloading), one on new approaches to chemical destruction of chemical agents, and one addressing thermal destruction of the agents. This report addresses the results of the study of the last area: thermal destruction of the agents.

## 1.1 Thermal Destruction of Toxic Chemical Agents

Thermal destruction is the most generally accepted method of destroying toxic organic materials for all cases where the toxicity is associated with the totality of the molecule rather than with a specific toxic element incorporated in the molecule. Incineration is used to destroy chlorinated hydrocarbons, pesticides, and various other toxic organic materials. Incineration is potentially capable of destroying any primarily organic material by oxidizing its carbon and hydrogen to $CO_2$ and water, and possibly altering the oxidation state of other elements in the molecule. The choice of incineration as a preferred method can be based on estimates or determinations of the required incineration conditions and an appraisal of the requirement for downstream pollution control needed to limit emissions of undesirable products of complete combustion. Some molecules, for example highly chlorinated aromatic compounds, may be sufficiently resistant to pyrolysis and oxidation to require very severe conditions in the incinerator for their destruction. The incinerated material may also form intermediate species thermally and oxidatively stable such as polynuclear aromatic species, that themselves require severe incineration conditions for their destruction. The incinerated materials may also contain elements whose compounds or physical form (e.g., $HCl$, $SO_2/SO_3$, fine particulates from "ash") are considered pollutants in the normal sense and require downstream (stack) controls to meet existing or anticipated pollution-control regulations.

With respect to the chemical agents GB, VX, and HD, available information indicates that these materials are thermally destroyed under relatively easily achieved conditions and that their structure does not suggest any unusual tendency to form resistant intermediate products. These agents are quite reasonable as fuels and their heat content is sufficient to achieve high flame temperatures (2500 F) without the need for auxiliary fuels.

These agents do, however, contain elements Cl, F, P, and S, whose emission is legally controlled and/or undesirable. Thus, either downstream pollution control is needed, or the incineration process must be accomplished in such a way as to capture these elements within the process.

All in all, thermal destruction of these chemical agents would appear to be easily accomplished with a minimum requirement for auxiliary energy inputs. Although emission controls are required (unless control can be integrated with the incineration process), the needed controls are within the state of the art. Incineration is thus a prime contender as a destruction process for these chemical agents.

## 1.2 Approach

The Thermal Process Development program which is summarized in this report involved five tasks:

Task 1. Planning and Baseline Review
Task 2. Literature Search
Task 3. Industrial Survey
Task 4. Concept Formulation and Evaluation
Task 5. Engineering and Economic Evaluation and Reporting.

In Task 1 the Army's baseline, a conceptualized system for thermal destruction of chemical agent munitions, was reviewed. Tasks 2 and 3 involved a review of literature and industry sources to identify technologies with potential for agent munitions destruction. In Task 4 an evaluation of these technologies was made and promising technologies were selected. In Task 5 an engineering and economic evaluation of the selected technologies was made and a Design Plan prepared outlining recommended further studies on four of the selected technologies.

Because of the volume of material presented in this report, generous use of appendices is made. For example, only a brief discussion of each of the processes evaluated in Task 5 is presented

in the Discussion section. Detailed individual discussions of the processes are given in the appropriate appendix.

# 2.0 DISCUSSION

## 2.1 Task 1. Planning and Baseline Review

Task 1 began with the organization of the project team, an initiation meeting with Army personnel and a visit to the Chemical Agent Munitions Disposal System (CAMDS) at Tooele, Utah. A conceptual facility based on the CAMDS facility and the proposed agent disposal facility for Johnston, Atoll was developed by the Army to provide a baseline against which technologies identified in the study could be compared. Figures 1A and 1B show in block-diagram form the four processing lines of the baseline concept.

The baseline concept was reviewed prior to its application in this program and a number of comments submitted to the Army.

The review team found it difficult to comment on the costs for buildings and equipment because the function and physical arrangement of equipment was not defined in the baseline. It was suggested that the information be presented in a different format to highlight the capacity (physical size and maximum munition processing rate for each munition), capital costs, and detailed operating costs for each of the major equipment items or areas within the two hypothetical facilities. This format would also facilitate use of the baseline in conducting process evaluations in subsequent tasks.

Several suggestions relative to the costs cited in the baseline were submitted during the first task. These suggestions/comments are summarized below.

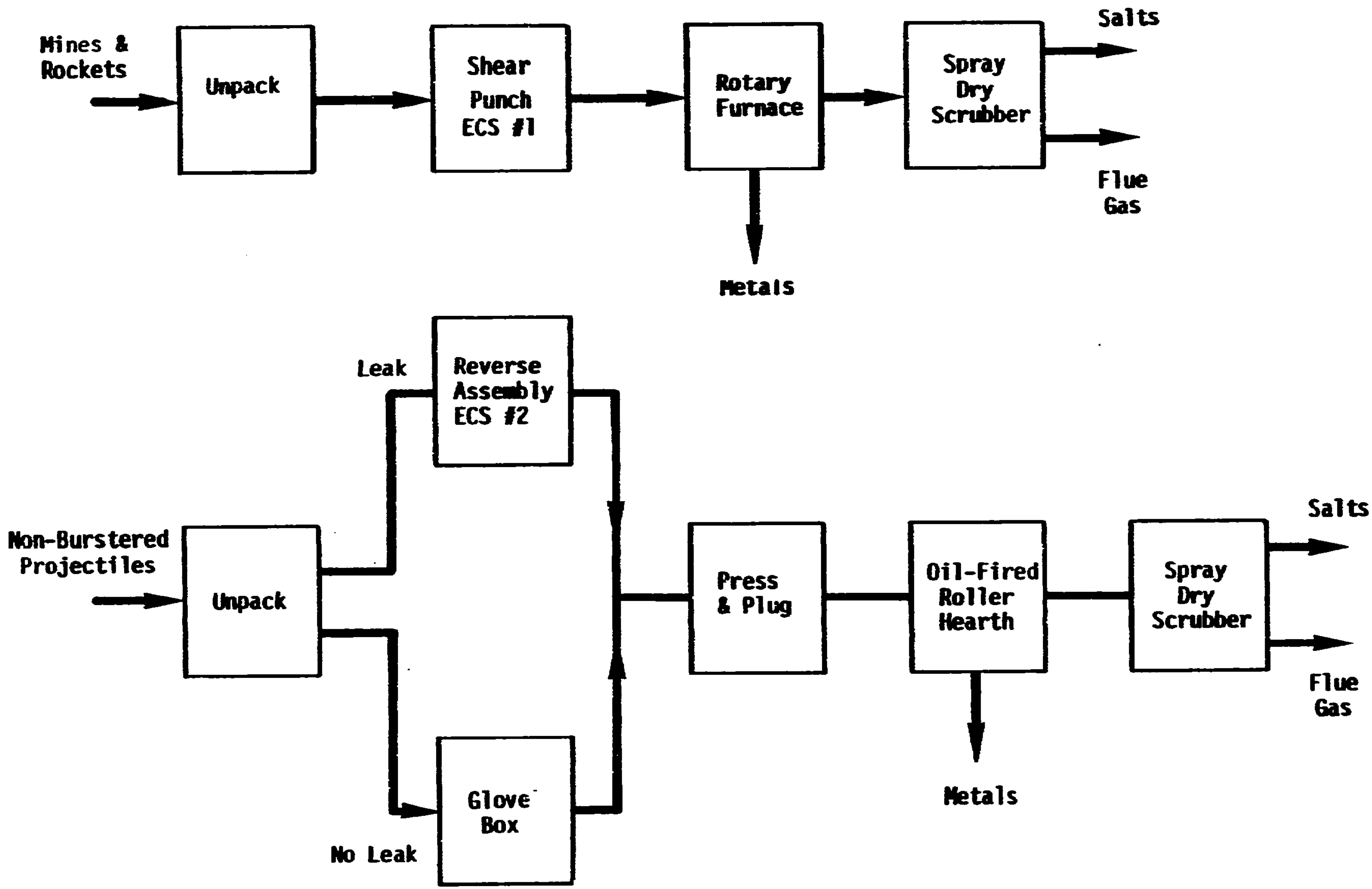



FIGURE 1A. FLOW DIAGRAM OF BASELINE

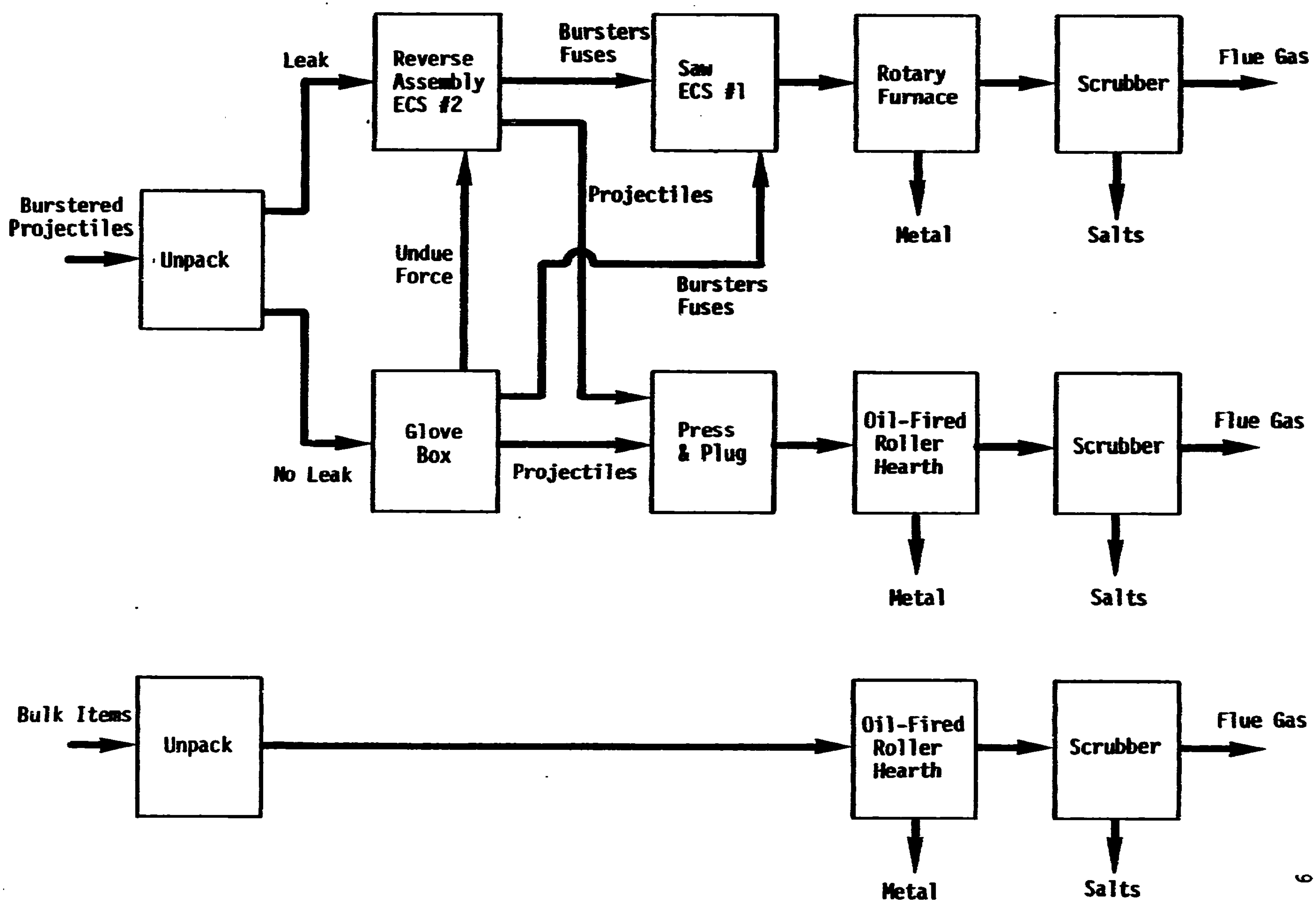



FIGURE 1B. FLOW DIAGRAM OF BASELINE

2.1.1 Main Demil Building. The Rockets/Mines/Dunnage/-Liquid Waste/Agent Explosive (R/M/D/Lw/A/E) Furnace Area, the Glove Box Area, and about 60 percent of the conveyor area should be built to resist explosions because the all-up munitions or segments processed in these areas are not inerted against accidental explosions. As a result, cost per square foot would increase from $90/ft$^2$ to $400/ft$^2$.

The control room, at $90/ft$^2$, did not appear to include special fire suppression equipment (e.g., a Halon or other dry system) and low vibration floors. It was suggested that these costs be included in this area (see following Manpower Section).

The laboratory appeared adequately sized for the number of persons designed. However, laboratory space of approximately double this area would be required to compensate for a larger analytical staff.

The salt storage area appeared adequate for only the salts from the rocket based on about 2 pounds of salt produced in the scrubber for each pound of agent, the given destruction rate of M-55 rockets, and a salt bulk density estimate of 60 lb/ft$^3$. It was suggested that this storage area be enlarged to accomodate both additional salt storage for total operation and metal parts storage, preferably for a 90-day period. No provision was found in the baseline for any metal parts storage subsequent to demiliterization operations.

The R/M/D/Lw/A/E Furnace appeared to be a hybrid between the rotary kiln incinerator at Hawthorne AAP and the Deactivation Furnace (DEAC Furnace) at CAMDS. The unit size is at least 50 percent larger than the DEAC at CAMDS (the R/M/D/Lw/A/E will process 30 rockets/hour; the DEAC was designed for only 20/hour) but appeared to cost less than the DEAC Furnace. To process liquid waste, to burn the agent from the rockets and mines, and to burn dunnage would require more advanced feed systems and possibly a more advanced design. The $4.6 million dollar cost cited in the baseline appeared to be low on this basis. The Bulk Item Furnace, as a direct analogue to the CAMDS Metal Parts Furnace, also appeared to be lower in cost than the CAMDS furnace.

Although the complexity of the R/M/D/Lw/A/E Furnace may be sufficient to prohibit a direct scale-up from the DEAC Furnace of CAMDS, there appeared to be no alternative. However, it was suggested that a scale factor of 0.6 not be used for this furnace due to the added complexity. The recommendation was made to scale the cost directly, based on furnace volume. The Bulk Item Furnace could be scaled from the CAMDS Metal Parts Furnace using the normal scale factor.

It was also suggested that the ultimate disposal costs be addressed in the baseline. This would make the baseline evaluations more useful on an actual cost basis.

2.1.2 Manpower. The glove box operation did not appear to be directly addressed in this analysis. Recommended labor could not be judged, other than by work involved. To process up to 75 munitions per hour by manual removal of fuzes or noseplugs would probably require 4 individuals, as these munitions have to be loaded, positioned, the nose plug or the fuze unscrewed, the explosive component removed, and the munition end plugged, all within a glove box.

The laboratory staff was thought to be understated. During the M34 demil operation at Rocky Mountain Arsenal, the lab was running at about 12 analytical persons per shift. CAMDS was 20 laboratory persons. Although 2/3 of these persons were to be involved in methods development, current practice requires all to be assigned to routine analysis since 4000 bubblers are analyzed weekly. It was recommended, therefore, that the laboratory staff be raised to at least 30 individuals.

As a result of these comments and comments from other contractors, the Army issued a revised baseline. The revised baseline was used to provide a standard for comparing processes in process evaluations and to provide technical data for preparation of cost estimates.

## 2.2 Task 2. Literature Search

Literature searches were carried out to identify technologies which might have application for thermal destruction of chemical agent munitions. The literature searches were:

a. Computerized Literature Search.

Sources: Chemical Abstracts
Engineering Index
Defense Technical Information Center
National Technical Information and Air
Pollution Technical Information Center

Search terms: destruction
high temperature
Incinerate (Truncated)
Pyrolysis
Thermal degradation

b. BZ Program Files (Contract No. DAAK11-81-C-0081)

Search terms: B agent
BZ agent
G agent
GB agent
Mustard agents
V agents
Vesicants
VX agent

c. Novel Processing Technology Files (Contract No. DAAK-11-81-C-0101)

Sources: Engineering Index
Chemical Abstracts
Defense Technical Information Center
National Technical Information Center
Smithsonian Science Information Exchange
Comprehensive Dessertation Index

Oil and Hazardous Materials Technical
Assistance Data System
Central Information Resarch Control

Search Terms:

arsenic agents
G agent
GA agent
GD agent
Lethal agents
Lewisite
Mustard agents
Nerve agents
Nitrogen mustards
V agent
VE agent
Vesicants
VX agent

d. Others: Battelle staff members, manual searches of Battelle and The Ohio State University libraries and catalogs, conversations with Cincinnati EPA officials, examinations of publications from recent symposiums and conferences, and references listed in reports received.

The literature searches turned up nearly 2000 references. These were reviewed and reduced to 139 pertinent references. The complete bibliography of these pertinent references is contained in Appendix A. These references provided leads for industrial contacts in Task 3 (Industrial Survey) and information for Task 4, Concept Formulation and Evaluation.

## 2.3 Task 3. Industrial Survey

Identification of thermal destruction processes from industrial sources was carried out by a variety of means. These included:

a. using industrial sources supplied by the Army

b. by advertisements in Commerce Business Daily

c. by news releases submitted to over 130 technical publications.

After reviewing the many responses received, a questionnarie was prepared and copies sent to industrial firms claiming to have applicable processes. A sample questionnaire will be found in Appendix B.

Some process information received was incomplete either because (a) the developer considered the process proprietary, (b) the process was in a preliminary state of development, or (c) the developer simply supplied limited information. In the first two cases little could be done except evaluate the process on the basis of the information available. In the later case the developer was subsequently contacted a sufficient number of times to obtain the required data.

To complete the information needed to evaluate certain processes, three plant visits were made. Plants visited were:

Rockwell International (Canoga Park, CA)

Westinghouse R&D Center (Pittsburgh, PA)

Pyro-Magnetics Corporation (Whitman, MA).

Process descriptions were prepared from data obtained in the industrial survey and from information developed in Task 3 (Literature Search). The processes are listed in the following sections and are described individually in Appendix C.

## 2.4 Task 4. Concept Formulation and Evaluation

The purpose of this task was to evaluate the thermal destruction processes identified in Tasks 2 and 3 and from this develop selected process concepts to be further evaluated in the Engineering and Economic evaluation portion of Task 5.

Forty-four concepts were developed in the previous tasks. These concepts are shown in Table 2 where they are listed according to the estimated development time (time for completion of required laboratory and pilot plant programs.)

The methodology used to evaluate the 44 concepts is shown in detail in Figure 2.

To begin the evaluation, the team was first familiarized with the criteria, the concepts, and the feed configurations. Applicable feed configurations for each process were then agreed on by the team. Next, each team member individually rated each process. After rating was complete, the team agreed on weighting factors for the criteria. The final rating for each process (and each applicable feed configuration) was then calculated.

### 2.4.1 Evaluation Criteria Factors

A list of pre-screening evaluation criteria supplied by the Army is given in Table 3. These criteria were slightly modified for use in theis evaluation. Two criteria identified by the Army, technical risk (I) and scalability (G), were combined into one criterion. A third criterion, process applicability (D) was eliminated because the method of evaluation used evaluated this factor separately.

The evaluation criteria used by the thermal process evaluations team members are given in Table 4. (The sub-criteria indicated in Table 3 by numbers were used in the evaluation although they are not shown in Table 4.)

TABLE 2. ESTIMATED DEVELOPMENT TIME

LESS THAN 5 YEARS

1. Rotary Kiln (cocurrent)/Molten Metal
3. Slagging Rotary Kiln (Ecorock)
5. IR Furnace
8. Fluidized-Bed
11. Liquid Injection
12. Cement Kiln
13. Rotary Kiln
14. Industrial Boiler
18. Single-Stage Molten Salt
19. Molten Salt/Metal Cleaning
20. Thermal Plasma Systems
21. Molten Metal
23. Mashed-Munition Fluidized-Bed
25. SUE Burner
27. Fluidized-Bed/Fume Incinerator (Inactive)
28. Sequential Fluidized-Bed ($E^3I$)
29. Plasma Arc Pyrolysis
30. Molten Metal/Slag (Thermal Download)
31. Rotary Kiln (Pyrolysis)
32. Fluidized-Bed (Thermal Download)
33. Resistance-Heated Fluidized-Bed (Pyrolysis)
35. Underground Detonation
37. Shaft Furnace/Scrap Cycle
41. Acid Dissolution/Incineration
42. Multi-Solid Fluidized-Bed
43. Vacuum Furnace
44. Induction Furnace

TABLE 2. (Continued)

5 TO 10 YEARS

2. Supercritical Fluid Download
4. Supercritical Oxidation
7. Spouted Bed
9. UV Photolysis
10. Solar Zapper
15. Internal Combustion Engine
16. Wet-Air Oxidation
17. High-Temperature Fluid Wall
24. Swinging Molten Salt
26. Swinging Molten Metal
36. Very Large Enclosure
38. Steam Pyrolysis (SEGAS)
39. Insitu Pyrolysis/Open Cavity

MORE THAN 10 Years

6. Magneto Hydrodynamics
22. Geothermal (Subduction Zone Burial)
34. Plasma Arc Vaporizer
40. Insitu Pyrolysis/Closed Cavity

FIGURE 2

METHODOLOGY FOR SELECTION OF PROCESS CONCEPTS

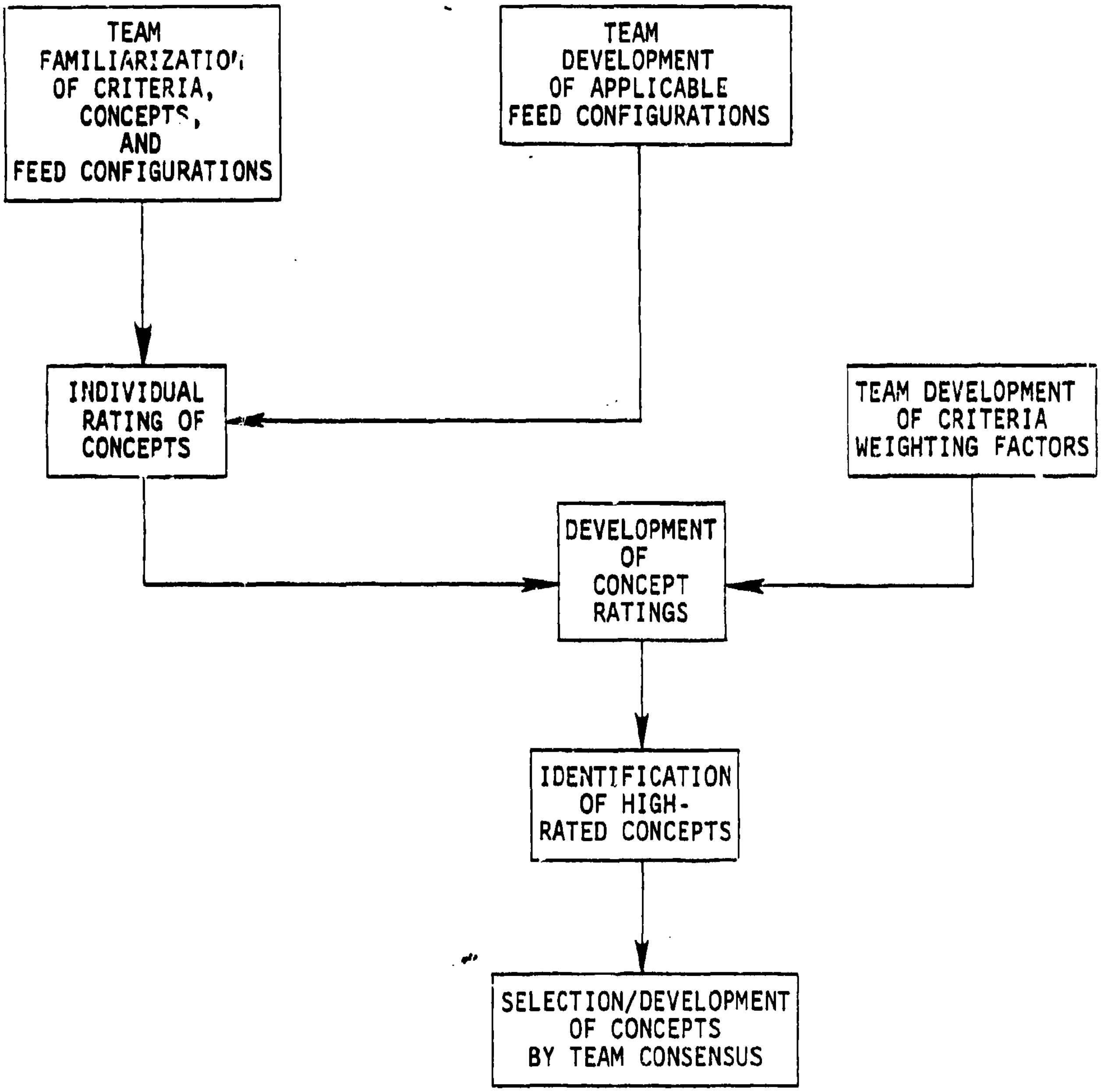


TABLE 3. ARMY PRE-SCREENING EVALUATION CRITERIA

A. COST
   1. Facility Capital
   2. Equipment Capital
   3. Operating
   4. Developmental
B. SAFETY
C. LIKELIHOOD OF DEVELOPMENT WITHIN 5 YEARS
D. PROCESS APPLICABILITY
   1. Agent Destruction
   2. Explosive
   3. Metal Part Decontamination
   4. Dunnage
E. PRE-PROCRESSING REQUIREMENTS
F. POST TREATMENT REQUIREMENTS
G. SCALABILITY TO 400-3000 POUNDS PER HOUR AGENT
H. FINAL WASTE CHARACTERISTICS AND ULTIMATE DISPOSAL
I. DEGREE OF TECHNICAL RISK
   1. Commercially Available (State of the Art)
   2. Pilot Scale
   3. Lab Scale
   4. Technology Gaps
J. RAM FACTORS
   1. Reliability
   2. Availability
   3. Maintainability
K. MATERIAL COMPATIBILITY PROBLEMS
L. ENERGY REQUIREMENTS AND SOURCE
M. EASE OF OPERATION
   1. Operability
   2. Flexibility
   3. Complexity

TABLE 4. MODIFIED EVALUATION FACTORS

1. SAFETY
2. LIKELIHOOD OF DEVELOPMENT WITHIN 5 YEARS
3. POST TREATMENT REQUIREMENTS
4. FINAL WASTE CHARACTERISTICS AND ULTIMATE DISPOSAL
5. DEGREE OF TECHNICAL RISK AND SCALABILITY
6. RAM FACTORS
7. MATERIAL COMPATIBILITY PROBLEMS
8. EASE OF OPERATION
9. ENERGY REQUIREMENTS AND SOURCE
10. COST

## 2.4.2 Feed Configurations

Feed configuration has a major impact on process selection and will, of course, greatly affect the total facility cost.

Eight feed configurations were identified by the Army. These configurations, together with modifications added (underlined phases) by evaluation team members are given in Table 5. The feed configurations are also shown schematically in Figure 3.

TABLE 5. MUNITION FEED CONFIGURATIONS

a. Stored munition configuration as is (i.e., loaded pallets).

b. Separate whole munitions.

c. Whole munition with limited modification (i.e., agent cavity and/or burster punctured).

d. Whole munition with agent removed. Explosive cavities open.

e. Whole munition with burster/explosive/propellant removed. Agent cavities open.

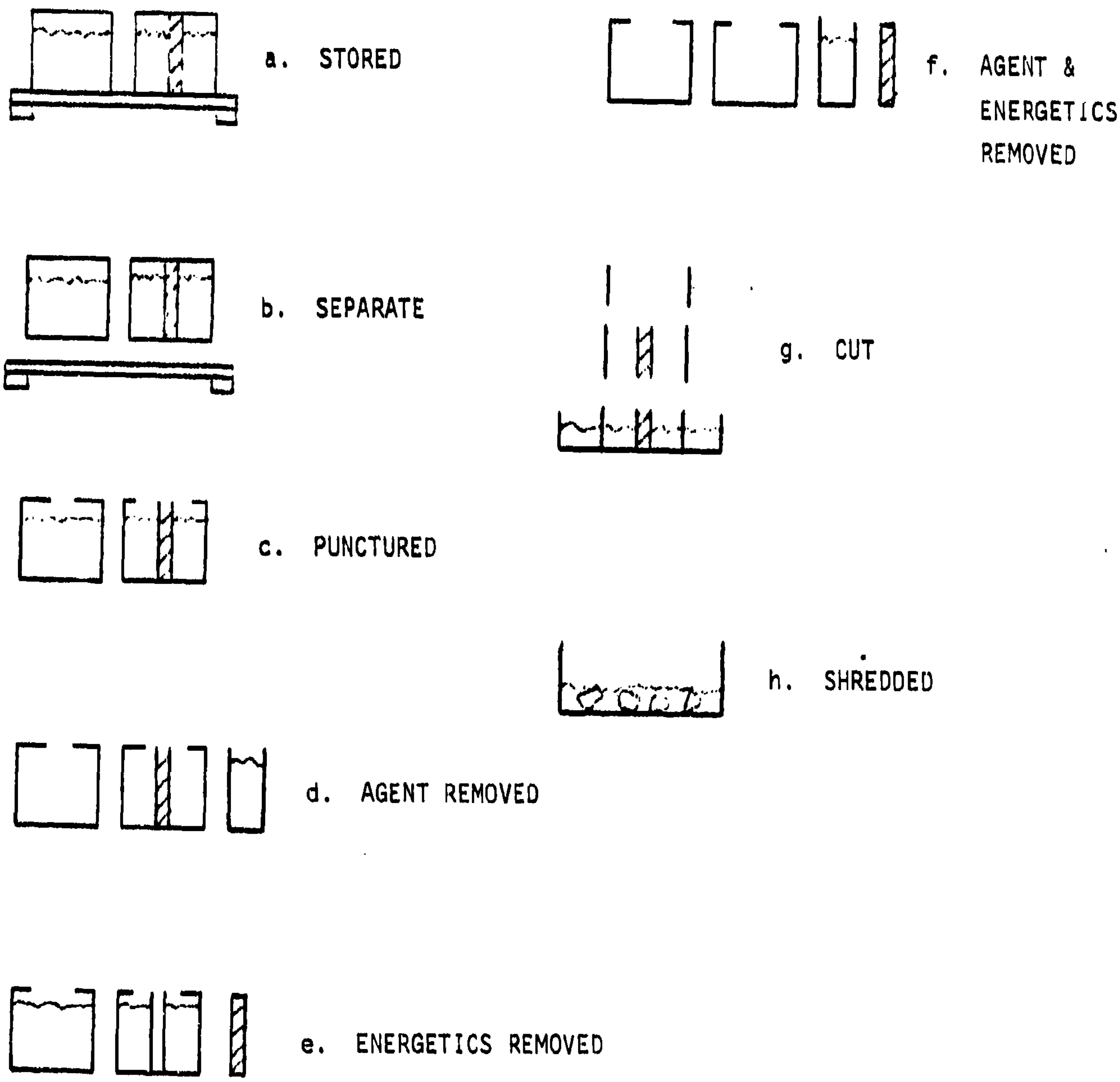
f. Whole munition with agent and burster/explosive/propellant removed.

g. Munition cut into distinct pieces, at least some of which exceed 6" in their maximum dimension.

h. Mixture of agent/explosives and metal pieces (metal pieces would be in a range of 1 to 6 inches).

For evaluation purposes, each feed configuration was broken down further into one or more of the following classifications:

FIGURE 3. MUNITION FEED CONFIGURATIONS



- E Explosive (munitions containing explosive and/or download explosives and propellants)
- N Nonexplosive (munitions with or without agent, ton containers with or without agent, inert parts, dunnage)
- P Propulsive items (primarily rockets, but consideration given to all-up artillery rounds)
- A Downloaded agent.

### 2.4.3 Concept Rating

To develop a numerical rating for each process it was necessary to poll the thermal process development team on the various concepts.

An evaluation form was prepared (see Figure 4) with evaluation criteria listed at the left and feed configuration/classification listed across the top.

Using the evaluation sheet, it was possible to evaluate each process (process, concept, or system) for each criterion for each of the possible applicable feed configuration/classification. (The applicable feed configuration/classifications were selected by consensus in meeting of project technical personnel.)

Evaluators were familiarized with the meanings of the terms involved (criteria, configurations, classifications) and were given written process descriptions for each of the 44 processes identified in Tasks 2 and 3. They were instructed to rate each process using a number from 0 to 10 for each criterion in the appropriate feed configuration/classification. A rating of 0 meant the process was most costly, least safe, highest technical risk, etc. A rating of 10 meant the opposite. When applicable, ratings were to be made comparative to the baseline, with a rating of 5 indicating the process was comparable to the baseline. When no comparison could be made because the baseline did not address that particular feed configuration/classification, a rating of 5 would be used to indicate an average value relative to all the systems.

## FIGURE 4. THERMAL PROCESS EVALUATION SHEET

PROCESS ______________________

FEED CONFIGURATION/CLASSIFICATION

| | WEIGHT | a | | | b | | | c | | | d | | | | e | | f | | | g | | h |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | E | N | P | E | N | P | E | N | P | E | N | P | A | E | N | E | N | A | N | E | E |
| 1. SAFETY | 13.1 | | | | | | | | | | | | | | | | | | | | | |
| 2. LIKELIHOOD OF DEVELOPMENT WITHIN 5 YEARS | 8.9 | | | | | | | | | | | | | | | | | | | | | |
| 3. POST TREATMENT REQUIREMENTS | 11.0 | | | | | | | | | | | | | | | | | | | | | |
| 4. FINAL WASTE CHARACTERISTICS & ULTIMATE DISPOSAL | 13.0 | | | | | | | | | | | | | | | | | | | | | |
| 5. DEGREE OF TECHNICAL RISK/ SCALABILITY | 10.1 | | | | | | | | | | | | | | | | | | | | | |
| 6. RAM FACTORS | 8.7 | | | | | | | | | | | | | | | | | | | | | |
| 7. MATERIAL COMPATIBILITY PROBLEMS | 6.4 | | | | | | | | | | | | | | | | | | | | | |
| 8. EASE OF OPERATION | 7.9 | | | | | | | | | | | | | | | | | | | | | |
| 9. ENERGY REQUIREMENTS & SOURCE | 5.4 | | | | | | | | | | | | | | | | | | | | | |
| 10. COST | 15.5 | | | | | | | | | | | | | | | | | | | | | |
| TOTAL/10 | | | | | | | | | | | | | | | | | | | | | | |
| WEIGHTED TOTAL/100 | | | | | | | | | | | | | | | | | | | | | | |

EVALUATOR ______________________

### 2.4.4 Criteria Factor Weights

To obtain a numerical rating for each process, it was necessary to develop weighting factors for each criterion. Team members were individually asked to provide their estimate based on their engineering experience of the weight that should be assigned to each factor. These results were averaged and normalized so that they totaled 100. The following results were obtained:

| Criteria Number (see Table 5) | Weight |
|---|---|
| 1 | 13.1 |
| 2 | 8.9 |
| 3 | 11.0 |
| 4 | 13.0 |
| 5 | 10.1 |
| 6 | 8.7 |
| 7 | 6.4 |
| 8 | 7.9 |
| 9 | 5.4 |
| 10 | 15.5 |

### 2.4.5 Process Concept Rating

Using the rating sheets and the evaluation criteria weighting factors, a numerical rating was developed for each process concept for the applicable feed configuration/classification. Figure 5 gives the rating results rounded to two significant figures. From Figure 5 it is difficult to visually identify the processes with high ratings. Furthermore, the averaged values do not provide an indication of the statistical significance of the rating.

Therefore, the rating results were further analyzed on a statistical basis using a FORTRAN program executed on the Battelle Control Data Corporation CYBER computer system. Only five concepts

| NO. | PROCESS | FEED CONFIGURATION/CLASSIFICATION | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | a | | | b | | | c | | | d | | | | e | | f | | | g | | h |
| | | E | N | P | E | N | P | E | N | P | E | N | P | A | E | N | E | N | A | N | E | E |
| 1 | Rotary Kiln (cocurrent)/Molten Metal | | | | | | | | | | | | | 5.4 | 5.6 | 5.4 | 5.5 | 5.4 | 5.3 | 5.3 | 5.2 | 5.4 |
| 2 | Supercritical Fluid Download | | | | | | | 4.3 | 4.4 | 4.2 | 4.4 | 4.5 | 4.3 | 4.5 | 4.4 | 4.4 | 4.5 | 4.6 | 4.5 | 4.4 | 4.2 | 4.9 |
| 3 | Slugging Rotary Kiln (Ecorock) | | | | | | | | | | | | | 5.1 | | | | | 5.1 | 4.9 | 4.8 | 4.8 |
| 4 | Supercritical Oxidation | | | | | | | | | | | | | 4.1 | 4.4 | | 4.4 | | 4.1 | | | |
| 5 | IR Furnace | | | | | | | | 5.2 | | | 5.6 | | 4.9 | 4.9 | 5.4 | 4.8 | 5.4 | 4.9 | 5.1 | 4.9 | 4.9 |
| 6 | Magneto Hydrodynamics | | | | | | | | | | | | | 4.0 | 3.9 | | 3.9 | | 4.0 | 3.9 | 3.7 | 3.9 |
| 7 | Spouted Bed | | | | | | | | | | | | | 4.9 | 4.9 | | 4.9 | | 4.9 | | 4.6 | 4.6 |
| 8 | Fluidized-Bed | | | | | | | 4.3 | 4.1 | 4.1 | 4.4 | 4.6 | 4.3 | 5.2 | 5.3 | 4.9 | 5.3 | 4.8 | 5.2 | 4.8 | 4.8 | 4.7 |
| 9 | UV Photolysis | | | | | | | | | | | | | 4.5 | | | | | 4.5 | | | |
| 10 | Solar Zapper | | | | | | | | | | | | | 4.1 | | | | | 4.1 | | | 4.0 |
| 11 | Liquid Injection | | | | | | | | | | | | | 5.6 | | | | | 5.6 | | | |
| 12 | Cement Kiln | | | | | | | | | | | | | 5.0 | 5.1 | 4.7 | 5.1 | 5.2 | 5.1 | 5.0 | 5.0 | 5.0 |
| 13 | Rotary Kiln | | | | | | | | | | | | | 5.1 | 5.2 | 4.6 | 5.2 | 5.1 | 5.1 | 4.8 | 4.7 | 5.1 |
| 14 | Industrial Boiler | | | | | | | | | | | | | 4.7 | | | | | 4.7 | | | |
| 15 | Internal Combustion Engine | | | | | | | | | | | | | 4.8 | | | | | 4.9 | | | |
| 16 | Wet-Air Oxidation | | | | | | | | | | | | | 4.3 | 4.3 | | 4.3 | | 4.3 | 4.0 | 3.6 | 4.1 |
| 17 | High-Temperature Fluid Wall | | | | | | | | | | | | | 4.8 | | | | | 4.8 | | | |
| 18 | Single-Stage Molten Salt | | | | | | | | | | | 4.9 | | 5.2 | 5.2 | 4.7 | 5.2 | 5.0 | 5.2 | 5.0 | 4.8 | 5.0 |
| 19 | Molten Salt/Metal Cleaning | | | | | | | | | | | 5.1 | | | | | | 5.2 | | | | |
| 20 | Thermal Plasma Systems | | | | | | | | | | | | | 5.0 | | | | 5.0 | | | | |
| 21 | Molten Metal | | | | | | | 4.6 | 4.7 | 4.4 | 4.9 | 5.2 | 4.8 | 4.9 | 5.1 | 4.6 | 5.2 | 5.3 | 4.9 | 5.0 | 4.9 | 5.0 |
| 22 | Geothermal (Subduction Zone Burial) | 5.3 | 5.3 | 5.3 | | | | | | | | | | | | | | | | | | |
| 23 | Washed-Munition Fluidized-Bed | | | | | | | | | | | | | 4.8 | 5.0 | | 5.0 | | 4.8 | 4.5 | 4.4 | 4.4 |
| 24 | Swinging Molten Salt | | | | | | | 4.3 | 4.7 | 4.2 | 4.4 | 5.0 | 4.3 | 5.0 | 4.9 | 4.7 | 5.0 | 4.8 | 4.9 | 4.7 | 4.7 | 4.8 |
| 25 | SUE Burner | | | | | | | | | | | | | 5.2 | | | | | 5.2 | | | |
| 26 | Swinging Molten Metal | | | | | | | 4.5 | 4.7 | 4.4 | 4.6 | 4.9 | 4.6 | 4.7 | 4.7 | 4.7 | 4.7 | 4.9 | 4.7 | 4.6 | 4.6 | 4.7 |
| 27 | Fluidized-Bed/Fume Incinerator (Inactive) | | | | | | | 4.4 | 4.6 | 4.3 | 4.4 | 4.8 | 4.3 | 4.7 | 4.9 | 4.6 | 4.8 | 4.8 | 4.7 | 4.5 | 4.5 | 4.5 |
| 28 | Sequential Fluidized-Bed ($E^3I$) | | | | | | | | | | | | | 5.0 | 5.3 | | 5.3 | | 5.0 | | | 4.7 |
| 29 | Plasma Arc Pyrolysis | | | | | | | 4.5 | 4.8 | 4.4 | 4.7 | 5.1 | 4.8 | 4.9 | 4.9 | 4.9 | 4.9 | 5.2 | 4.9 | 4.8 | 4.7 | 4.7 |
| 30 | Molten Metal/Slag (Thermal Download) | | | | | | | 4.3 | 4.6 | 4.3 | 4.6 | 5.1 | 4.6 | 4.8 | 4.8 | 4.7 | 4.8 | 5.1 | 4.8 | 4.5 | 4.5 | 4.6 |
| 31 | Rotary Kiln (Pyrolysis) | | | | | | | 4.5 | 4.6 | 4.4 | 4.6 | 5.0 | 4.6 | 4.7 | 4.8 | 4.8 | 4.8 | 5.0 | 4.7 | 4.7 | 4.7 | 4.7 |
| 32 | Fluidized-Bed (Thermal Download) | | | | | | | 4.5 | 4.8 | 4.5 | 4.6 | 5.2 | 4.6 | 5.0 | 5.1 | 4.9 | 5.1 | 5.2 | 5.0 | 4.9 | 4.9 | 4.9 |
| 33 | Resistance-Heated Fluidized-Bed (Pyrolysis) | | | | | | | 4.3 | 4.4 | 4.2 | 4.6 | 5.0 | 4.6 | 4.8 | 5.0 | 4.6 | 5.0 | 5.0 | 4.8 | 4.7 | 4.6 | 4.7 |
| 34 | Plasma Arc Vaporizer | | | | 4.0 | 4.1 | 4.0 | 4.1 | 4.3 | 4.1 | 4.2 | 4.4 | 4.2 | 4.5 | 4.5 | 4.2 | 4.3 | 4.4 | 4.5 | 4.3 | 4.3 | 4.3 |
| 35 | Underground Detonation | 6.2 | 6.2 | 6.2 | | | | | | | | | | | | | | | | | | |
| 36 | Very Large Enclosure | 4.4 | 4.3 | 4.3 | 4.5 | 4.4 | 4.3 | 4.5 | 4.5 | 4.4 | 4.5 | 4.6 | 4.4 | 4.5 | 4.5 | 4.5 | | | | | | |
| 37 | Shaft Furnace/Scrap Cycle | | | | 4.5 | 4.5 | 4.5 | 4.6 | 4.6 | 4.6 | | | | | | | | | | | | |
| 38 | Steam Pyrolysis (SEGAS) | | | | | | | | | | | | | 4.5 | | | | | 4.5 | | | |
| 39 | Inside Pyrolysis/Open Cavity | | | | | | | 3.7 | 4.1 | 3.7 | | | | | | | | | | | | |
| 40 | Insitu Pyrolysis/Closed Cavity | 3.5 | 3.6 | 3.5 | 3.5 | 3.6 | 3.5 | | | | | | | | | | | | | | | |
| 41 | Acid Dissolution/Incineration | | | | 5.0 | 5.0 | 5.0 | | | | | | | | | | | | | | | |
| 42 | Multi-Solid Fluidized-Bed | | | | | | | 4.3 | 4.4 | 4.2 | 4.4 | 4.5 | 4.3 | 4.9 | 4.8 | 4.5 | 5.0 | 4.9 | 5.0 | 4.8 | 4.7 | 4.7 |
| 43 | Vacuum Furnace | | 4.7 | | 4.7 | | | 4.8 | 4.9 | 4.6 | | 5.0 | 4.6 | 4.9 | 4.9 | 4.8 | 4.9 | 5.0 | 4.8 | 4.9 | 5.0 | 5.0 |
| 44 | Induction Furnace | | | | | | | | 5.1 | | | 5.6 | | 4.9 | 4.9 | 5.4 | 4.9 | 5.0 | 4.9 | 4.6 | 4.1 | 4.1 |

FIGURE 5. AVERAGED CONCEPT RATINGS

were found to have ratings in excess of two standard deviations ($\sigma$) above five. (These are indicated by large black dots in Figure 6.)

As a final step in the selection of concepts, the team met to review the thinking that went into the evaluation process. In some instances, a low-rated concept had one reviewer who had rated it high. Conversely, in some instances, a high-rated concept had one reviewer who rated it low. It was felt that perhaps the reviewer who rated a concept lower or higher than the rest of the team knew of some significant disadvantage the concept had which the rest of the team was not aware of, or had conceived of some modification or attribute of the concept that would make it particularly attractive. In the final review meeting, each concept was discussed and comments elicited from low- and high-rating reviewers to insure that the concept should be accepted or rejected as indicated by the balloting. As a result of that meeting, the following concepts were selected for the Task 5 evaluation:

| Process | Probable Feed Configuration |
|---|---|
| Underground Detonation | a |
| *Shaft Furnace | b/c |
| *Acid Roaster (acid dissolution) | b |
| Molten Metal | c/e or h |
| *IR Vacuum Furnace | c |
| Rotary Kiln | c/e or g/h |
| Fluidized-Bed | e or h |
| Molten Salt | h |

The above list contains three concepts, identified by asterisks, which were not rated high in the balloting (Shaft Furnace,

| NO. | PROCESS | FEED CONFIGURATION/CLASSIFICATION | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | a | | | b | | | c | | | d | | | e | | | f | | g | | | h |
| | | E | N | P | E | N | P | E | N | P | E | N | P | A | E | N | E | N | A | N | E | E |
| 1 | Rotary Kiln (cocurrent)/Molten Metal | | | | | | | | | | | | | ● | ● | • | ◆ | ● | • | ● | ● | ◆ |
| 2 | Supercritical Fluid Download | | | | | | | ◇ | ◇ | ◇ | ◇ | ◇ | ◇ | ◇ | ◆ | ◇ | ◆ | ◇ | ◇ | ◇ | ◇ | ◇ |
| 3 | Slugging Rotary Kiln (Ecorock) | | | | | | | | | | | | | ◇ | | | | | ◇ | ◆ | ◆ | ◆ |
| 4 | Supercritical Oxidation | | | | | | | | | | | | | ◇ | ◇ | | ◇ | | ◇ | | | |
| 5 | IR Furnace | | | | | | | | ◆ | | | ◆ | | ◇ | ◆ | ◆ | ◆ | ◆ | ◇ | ⊙ | ◇ | ⊙ |
| 6 | Magneto Hydrodynamics | | | | | | | | | | | | | · | · | | · | | · | · | · | · |
| 7 | Spouted Bed | | | | | | | | | | | | | ◆ | ◆ | | ◆ | | ◆ | | ◆ | ◆ |
| 8 | Fluidized-Bed | | | | | | | · | ⊙ | ⊙ | · | ◇ | ⊙ | ⊙ | ◇ | ⊙ | ◇ | ◇ | ⊙ | ◆ | ◆ | ◇ |
| 9 | UV Photolysis | | | | | | | | | | | | | · | | | | | · | | | |
| 10 | Solar Zapper | | | | | | | | | | | | | · | | | | | · | | | · |
| 11 | Liquid Injection | | | | | | | | | | | | | ◆ | | | | | ◆ | | | |
| 12 | Cement Kiln | | | | | | | | | | | | | ◇ | ◇ | ◆ | ◇ | ◇ | ◇ | ◆ | ◇ | ◆ |
| 13 | Rotary Kiln | | | | | | | | | | | | | ◆ | ◇ | ⊙ | ◇ | ◇ | ◆ | ◇ | ◇ | ◇ |
| 14 | Industrial Boiler | | | | | | | | | | | | | ◇ | | | | | ◇ | | | |
| 15 | Internal Combustion Engine | | | | | | | | | | | | | · | | | | | · | | | |
| 16 | Wet-Air Oxidation | | | | | | | | | | | | | · | · | | · | | · | · | ⊙ | · |
| 17 | High-Temperature Fluid Wall | | | | | | | | | | | | | ◆ | | | | | ◆ | | | |
| 18 | Single-Stage Molten Salt | | | | | | | | | | | ◇ | | • | ◆ | ◇ | ◆ | ◇ | • | ◆ | ◇ | ◆ |
| 19 | Molten Salt/Metal Cleaning | | | | | | | | | | | ◇ | | | | | | ◇ | | | | |
| 20 | Thermal Plasma Systems | | | | | | | | | | | | | ◇ | | | | | ◇ | | | |
| 21 | Molten Metal | | | | | | | ◆ | • | ◇ | ◆ | • | ◆ | ● | ◆ | ◇ | ◆ | ◆ | ● | ◆ | ◆ | ● |
| 22 | Geothermal (Subduction Zone Burial) | ◆ | ◆ | ◆ | | | | | | | | | | | | | | | | | | |
| 23 | Washed-Munition Fluidized-Bed | | | | | | | | | | | | | ◇ | ◇ | | ◇ | | ◇ | ⊙ | ⊙ | ◇ |
| 24 | Swinging Molten Salt | | | | | | | · | ◇ | · | · | ◇ | · | ◇ | ◇ | ◇ | ◆ | ◇ | ◇ | ◇ | ◇ | ◇ |
| 25 | SUE Burner | | | | | | | | | | | | | ◆ | | | | | ◆ | | | |
| 26 | Swinging Molten Metal | | | | | | | ◆ | ◇ | ◇ | ◇ | ◇ | ◇ | ◆ | ◆ | ◆ | ◆ | ◇ | ◇ | ◆ | ◆ | ◆ |
| 27 | Fluidized-Bed/Fume Incinerator (Inactive) | | | | | | | ◇ | ◇ | ◇ | ◇ | ◇ | ◇ | ◆ | ◇ | ◇ | ◇ | ◇ | ◆ | ◇ | ◇ | ◇ |
| 28 | Sequential Fluidized-Bed (E$^3$I) | | | | | | | | | | | | | ◇ | ◇ | | ◆ | | ◇ | | | ◇ |
| 29 | Plasma Arc Pyrolysis | | | | | | | ◇ | ◇ | ◇ | ◇ | ◆ | ◇ | • | ◇ | ◇ | ◇ | ◆ | ◆ | ◆ | ◆ | ◆ |
| 30 | Molten Metal/Slag (Thermal Download) | | | | | | | ◇ | ◇ | ◆ | ◇ | ◆ | ◇ | ◇ | ◆ | ◆ | ◆ | ◆ | ◇ | ◆ | ◇ | ◆ |
| 31 | Rotary Kiln (Pyrolysis) | | | | | | | ◇ | • | ◇ | ◇ | ◆ | ◇ | ● | ◇ | • | ◇ | ◆ | ● | ◇ | ◆ | ◇ |
| 32 | Fluidized-Bed (Thermal Download) | | | | | | | ◇ | ◆ | ◇ | ◇ | • | ◇ | ◇ | ● | ◇ | ● | • | ◇ | • | • | • |
| 33 | Resistance-Heated Fluidized-Bed (Pyrolysis) | | | | | | | ◆ | ◆ | ⊙ | ◇ | • | ◇ | • | ◆ | ◇ | ◆ | • | • | ◇ | ◇ | ◇ |
| 34 | Plasma Arc Vaporizer | | | | ⊙ | ⊙ | ⊙ | ⊙ | ⊙ | ⊙ | ⊙ | · | ⊙ | ⊙ | ⊙ | ⊙ | ⊙ | · | ⊙ | ⊙ | ⊙ | ⊙ |
| 35 | Underground Detonation | ● | ● | ● | | | | | | | | | | | | | | | | | | |
| 36 | Very Large Enclosure | ⊙ | ⊙ | ⊙ | ⊙ | ⊙ | · | ⊙ | ⊙ | ⊙ | ⊙ | ⊙ | ⊙ | ◇ | ◇ | ⊙ | | | | | | |
| 37 | Shaft Furnace/Scrap Cycle | | | | ⊙ | ⊙ | ⊙ | ⊙ | ⊙ | ⊙ | | | | | | | | | | | | |
| 38 | Steam Pyrolysis (SEGAS) | | | | | | | | | | | | | · | | | | | · | | | |
| 39 | Insitu Pyrolysis/Open Cavity | | | | | | | · | · | · | | | | | | | | | | | | |
| 40 | Insitu Pyrolysis/Closed Cavity | · | ⊙ | · | · | ⊙ | · | | | | | | | | | | | | | | | |
| 41 | Acid Dissolution/Incineration | | | | ◆ | ◆ | ◆ | | | | | | | | | | | | | | | |
| 42 | Multi-Solid Fluidized-Bed | | | | | | | · | ⊙ | · | · | · | ⊙ | ◆ | ◇ | · | ◇ | · | ◆ | ◇ | ◇ | ◇ |
| 43 | Vacuum Furnace | | ◇ | | ◇ | | | ⊙ | · | ⊙ | | ⊙ | · | ◇ | ⊙ | · | · | · | · | · | · | · |
| 44 | Induction Furnace | | | | | | | | ◆ | | | ◆ | | ◇ | ◆ | ◆ | ◆ | ◆ | ◇ | ⊙ | ◇ | ⊙ |

● > 2 σ  • 1 to 2 σ  ◆ 0 to 1 σ  ◇ -1 to 0 σ  ⊙ -2 to -1 σ  · < -2 σ

FIGURE 6. THERMAL CONCEPTS RATED IN TERMS OF STANDARD DEVIATION INCREMENTS

Acid Roaster, and IR Vacuum Furnace). These three concepts were added to the above list as a result of the team consensus after reviewing comments individual team members had on significant advanages of these processes. (None of the five concepts selected as a result of the statistical analysis were rejected in this meeting.) One of the significant reasons for including these additional three concepts was that each provided a basis for minimizing the degree of downloading.

It will be noted that in some cases in the list of concepts (Appendix C), there are several variations presented for an individual process. For example, concepts 7, 8, 23, 27, 28, 32, 33, and 42 are all fluidized-beds. Only concept 32 received an acceptably high rating. However, the significant features of all similar concepts were considered when developing a final concept for evaluation in Task 5. That is, all eight fluidized-bed concepts were reviewed by the team to develop a final optimum concept for Task 5. The final fluidized-bed concept is not exactly any one of the eight concepts but includes those features of all eight which the team believed to provide the best final concept. The same was done with the other final eight concepts where appropriate.

As noted in Table 2, all eight concepts selected were judged by the team to be capable of development within 5 years.

## 2.5 Task 5. Engineering and Economic Evaluation and Reporting

The purpose of Task 5 was to evaluate and select concepts to be recommended for further development in a pilot scale program.

Task 5 consisted of three activities:

- Engineering and economic evaluation of the eight concepts selected in Task 4.
- Preparation of a design plan for further laboratory studies of four of the concepts.
- Preparation of the final report.

## 2.5.1 Engineering and Economic Evaluation of the Eight Concepts Selected in Task 4

The engineering evaluation of the eight concepts consisted of a process description and an analysis addressing several factors:

- Systems feed requirements
- Pollution abatement system
- Ultimate disposal
- System concept advantages
- System concept disadvantages
- System concept knowledge gaps
- Safety
- Likelihood of development within 5 years
- Scalability to 400-3000 pounds per hour of agent
- Degree of technical risk
- RAM factors
- Material Compatibility problems
- Energy requirements and source
- Ease of operation.

The economic analysis considered facility cost, capital equipment, operating cost, development cost, and operating time to develop a total life cycle cost. The analysis was carried out using techniques which were internally consistant and consistant with the baseline study, and was reviewed for accuracy by experienced personnel. Therefore, while the absolute value of the numbers generated may be subject to some question, the relative values are believed to be well within the range acceptable for preliminary estimates of this kind and are sufficient for making the currently required economic judgments.

Each of the factors for the engineering analysis and the economic analysis for each of the eight selected concepts is described in detail in the appropriate appendicies. Therefore, only brief discussions of the concepts with highlights of the engineering and economic evaluation follow:

To provide a pictorial comparison of the process, life cycle costs the cost to demilitarize the inventory at a single site or the cost to demilitarize the entire inventory (collocated site) are shown graphically.

2.5.1.1 Acid Roaster. In the acid roasting concept, whole munitions/items (feed configuration b) are placed in dissolution tanks where they are contacted with acid which dissolves the metal container and frees agent and degrades energetic materials. The resulting slurry is pumped to a roaster where agents (and their hydrolysis products) and degraded energetic materials are thermally destroyed. Acid gases recovered from the roaster are recycled to the dissolution tanks.

The acid roasting concept has several advantages over most other processes evaluated. No munitions downloading is required; no mechanical preparation or disassembly, other than possibly paint removal is necessary. Furthermore, all the processing steps following the dissolution step are commercially available technology.

Knowledge gaps are mainly those associated with the acid dissolution step. The effect of the acid environment on the energetic mateials and the handling of those materials are the primary concern.

Total life cycle costs range from $21.0 million to $31.1 million for single site and from $87.2 million to $134.3 million for collocated site. Life cycle costs are presented in Figures 7 and 8.

A detailed engineering and economic analysis on the Acid Roaster process will be found in Appendix D.

2.5.1.2 Rotary Kiln. Two variations of the Rotary Kiln concept were evaluated. The first concept is based on a single size large kiln; the kiln size is independent of feed rate and is sufficiently large enough to handle the largest munition/items in the inventory (ton containers). The second concept is based on the

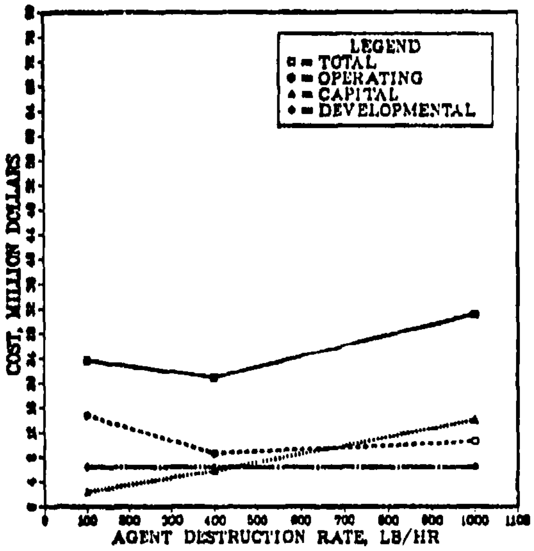



FIGURE 7. ACID ROASTER CONCEPT
Life Cycle Cost Curves
Single Site, Feedstock b

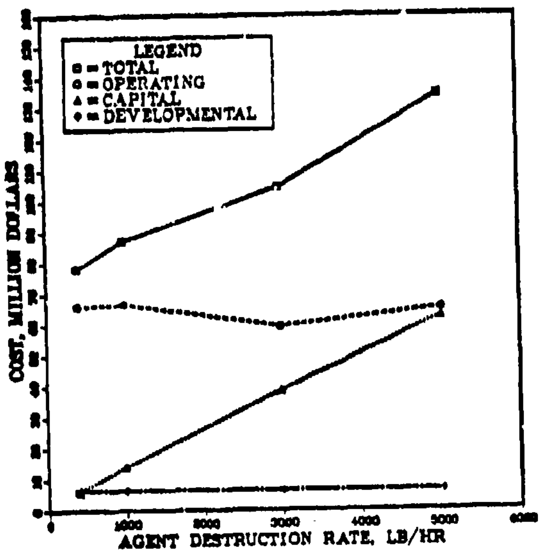



FIGURE 8. ACID ROASTER CONCEPT
Life Cycle Cost Curves
Collocated Site, Feedstock b

selection of a kiln size proportional to the feed rate and independent of munition/item size. This latter concept is called the proportional kiln concept.

The large rotary kiln is capable of handling burstered munitions with the explosive removed and agent cavity opened (configure-action e) and non-burstered munitions with agent cavity opened (configuration c). At the smaller sizes, the proportional kiln will handle only cut-up munitions (configurations g and h). At the 5000 lb/hr rate the proportional kiln is the same as the large kiln and can handle configuration e/c.

The large rotary kiln system is a simple system to operate because it consists of one major furnace and an afterburner that will handle all munitions in the appropriate feedstock configuration. The rotary kiln is a state-of-the-art device for incineration of hazardous wastes and rotary kilns of the size required for the demilitarization process have been built. There is thus a background of industrial experience which applys directly to the development of the rotory kiln for chemical agent/munition demilitarization and the technical risk is consequently minimized. The rotary kiln process is an excellent candidate for fast-track development.

Rotary kiln technology is probably the most advanced of any of the concepts studied. Knowledge gaps center around refractory life as affected by chemical attack and abraision from the munitions.

For the large rotary kiln, total life cycle costs range from \$31.3 million to \$63.8 million for single site and from \$37.2 million to \$67.5 million for collocated site. For the proportional kiln total life cycle costs range from \$13.2 million to \$17.8 millin for single site and from \$27.3 million to \$32.3 million for collocated site. Life cycle costs are presented in Figures 9 through 12.

A detailed engineering and economic analysis on the rotary kiln process will be found in Appendix E.

<u>2.5.1.3 Molten Metal</u>. The molten metal concept is based on technology commonly used in the iron and steel industry. In this

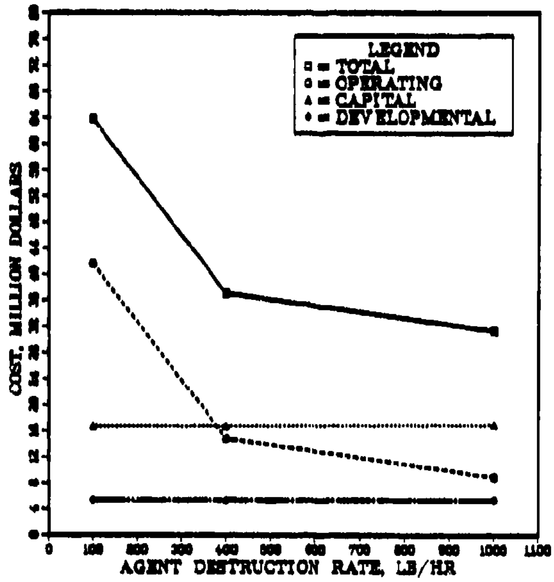



FIGURE 9. LARGE ROTARY KILN CONCEPT
Life Cycle Cost Curves,
Single Site, Feedstock c/e

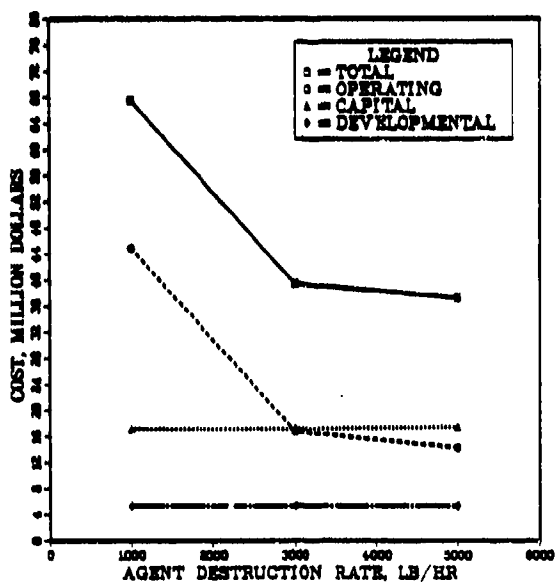



FIGURE 10. LARGE ROTARY KILN CONCEPT
Life Cycle Cost Curves,
Collocated Site, Feedstock c/e

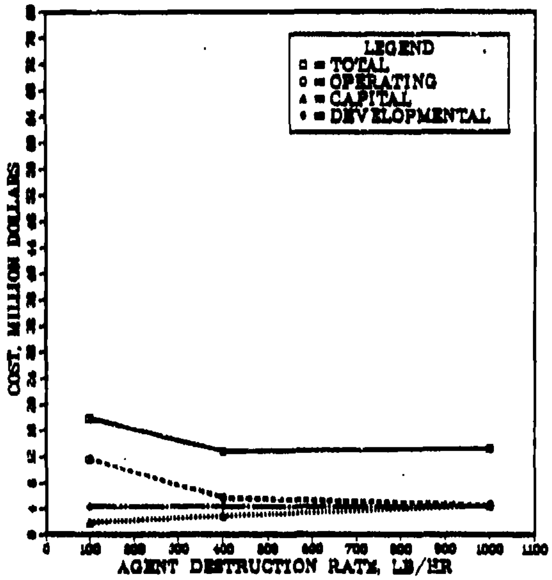



FIGURE 11. PROPORTIONAL ROTARY KILN CONCEPT
Life Cycle Cost Curves,
Single Site, Feedstock g/h

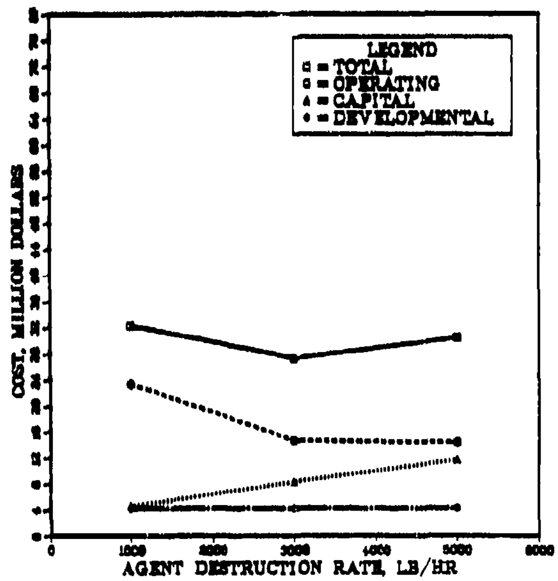



FIGURE 12. PROPORTIONAL ROTARY KILN CONCEPT
Life Cycle Cost Curves,
Collocated Site, Feedstock g/h

process agent is volatilized in a voltalization chamber. The volatilized agent passes through a hot plasma air stream where it is pyrolized. Pyrolized agent and metal parts pass into a molten metal/slag chamber where metal is melted and removed. The gases pass out through an afterburner and scrubbing system.

This concept is designed to handle agent-only inventory in feed configuration c (agent cavity opened) and inventory containing energetic materials in feed configuration e (burster/propellant removed).

Aside from having the potential for extremely high agent destruction efficiencies, the molten metal concept uses state-of-the-art components. The process is simple, versatile, and flexible. There are no liquid wastes.

Knowledge gaps center around materials compatibility considerations.

Total life cycle costs range from $15.0 million to $18.9 million for single site and from $37.4 million to $48.7 million for collocated site. Life cycle costs are presented in Figures 13 and 14.

A detailed engineering and economic analysis on the molten metal process will be found in Appendix F.

2.5.1.4 Fluidized-Bed. The fluidized-bed is capable of handling several classes of munitions feed. In the engineering and economic analysis the fluidized-bed was designed to handle munitions with the explosive removed and the agent cavity opened (configuration e) as well as feed from a munition shredder (configuration h). At low feed rates of configuration e, a volatilization chamber is recommended for volatilizing agent from ton containers and other large items. Removal of solids would be through the bottom of the bed with a moving bed system and a ram type shear.

Two of the major advantages of the concept are its ability to process munitions with minimal downloading relative to that required by the baseline and its low requirement for supplemental fuel. Furthermore, certainly for processing munitions of feedstock

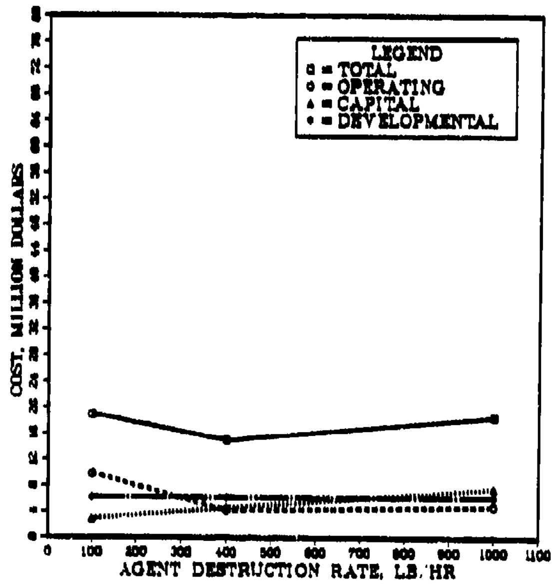



FIGURE 13. MOLTEN METAL CONCEPT
Life Cycle Cost Curves,
Single Site, Feedstock c/e

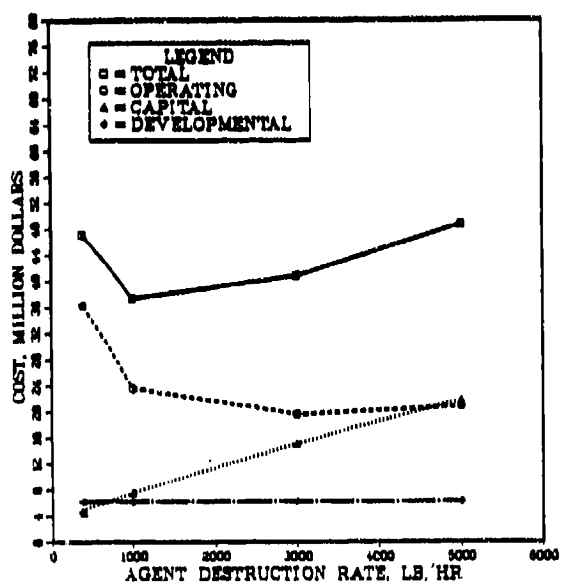



FIGURE 14. MOLTEN METAL CONCEPT
Life Cycle Cost Curves,
Collocated Site, Feedstock c/e

configuration h, the system is much simpler, has less mechanical parts, and will probably be more reliable than other systems studied.

Fluidized beds will also have advantages associated with their tolerance of fuel properties and short-term irregulaties in fuel feed rates, their ability to accept solid and unatomized liquid fuels (and thus be tolerant of suspended solids and polymerized agent remaining in certain munitions), and their ability to operate at relatively low peak temperatures.

If an active bed can be used to control emissions and/or if the freebroad can perform the function of an afterburner, the downstream processing will be greatly simplified.

Knowledge gaps center around metal removal from the bed, bed agglomeration, and heat transfer rates. The system is considered safe.

For feedstock e, total life cycle costs range from $17.6 million to $20.7 million for single site and from $32.3 million to $39.2 million for collocated site. Costs are $2 to $3 million lower for feed stock h. Life cycle costs are presented in Figures 15 through 18.

A detailed engineering and economic analysis on the fluidized-bed process will be found in Appendix G.

<u>2.5.1.5 IR Vacuum Furnace</u>. The IR (Infrared) vacuum furnace concept was devised primarily as a method of avoiding downloading of explosives from the munitions. In a vacuum, explosives burn rapidly rather than detonate. However, this is a complex mechanism and localized high pressure areas caused by partial containment or shielding could result in detonations. (This uncertainty and the technical risks involved were the primary factors in rejecting this concept from consideration for further development.)

In this process, munitions in configuration c are placed in a tray and passed into a vacuum oven. Here they are heated and decontaminated by pyrolysis. Vacuum is maintained by a liquid seal pump which also acts as a scrubber for the acid gases. The exhaust gases

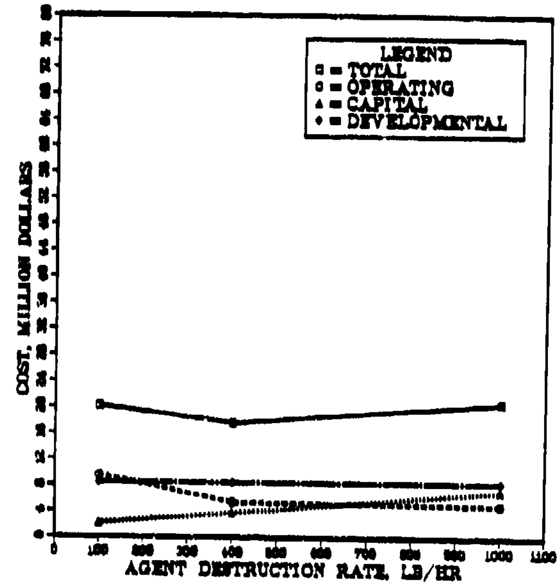



FIGURE 15. FLUIDIZED-BED CONCEPT
Life Cycle Cost Curves
Single Site, Feedstock e

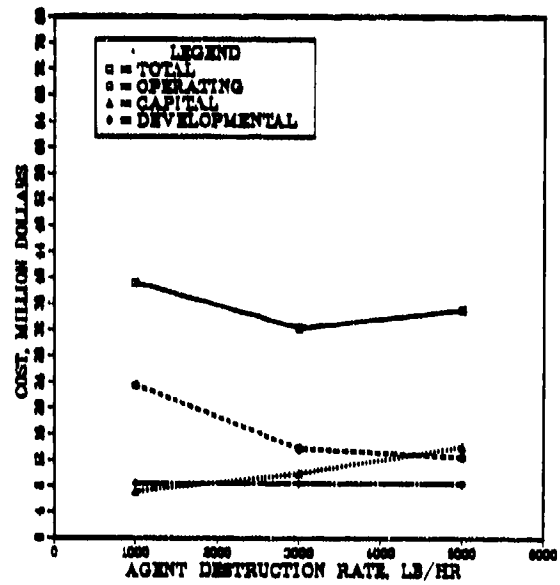



FIGURE 16. FLUIDIZED-BED CONCEPT
Life Cycle Cost Curves
Collocated Site, Feedstock e

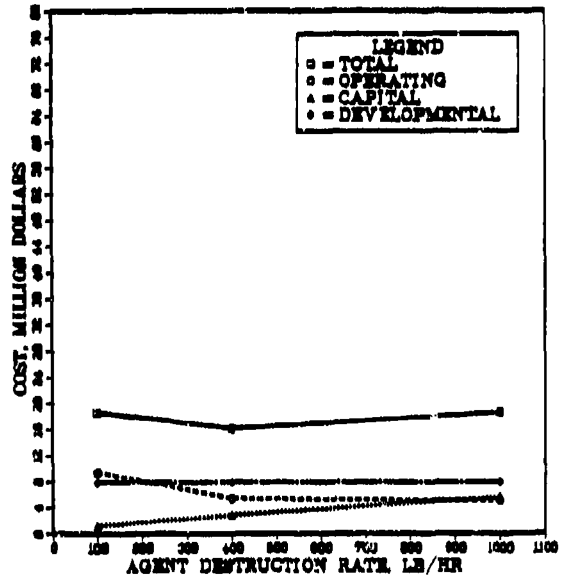



FIGURE 17. FLUIDIZED-BED CONCEPT
Life Cycle Cost Curves
Single Site, Feedstock h

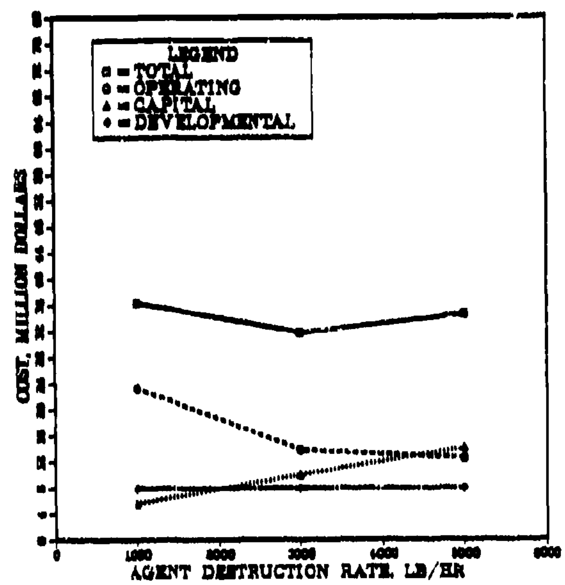



FIGURE 18. FLUIDIZED-BED CONCEPT
Life Cycle Cost Curves
Collocated Site, Feedstock h

pass through an afterburner (to burn pyrolysis products) and a spray dryer (to dry salts generated in the liquid seal pump).

Knowledge gaps include the questions of detonation in a vacuum, action of the vacuum pump as a scrubber, and rate of decomposition of agent in vacuum.

Total life cycle costs range from $17.1 million to $23.5 million for single site and from $35.5 million to $41 million for collocated site. Life cycle costs are presented in Figures 19 and 20.

A detailed engineering and economic analysis on the IR vacuum furnace process will be found in Appendix H.

2.5.1.6 Shaft Furnace. In the shaft furnace concept, munitions are heated in a shaft furnace filled with metal scrap. The scrap serves as a buffer to shield the vessel walls, inlet and discharge from the fragments and blast wave from exploding/detonating munitions. The economic analysis of the shaft furnace concept indicated that it was probably an acceptable concept, at least for the collocation facility. However, the engineering analysis indicated that the technical risks associated with the shaft furnace concept were substantial.

Knowledge gaps include the question of blast wave loading on the shaft furnace walls. If the scrap charge transmits the impulse loading to the walls the process is probably not technically feasbile. It could be very costly to determine this in a development program.

Total life cycle costs range from $31.9 million to $50.5 million for single site and from $100.0 million to $215.0 million for collocated site. Life cycle costs are presented in Figures 21 and 22. This concept was eliminated from further consideration.

A detailed engineering and economic analysis on the shaft furnace process will be found in Appendix I.

2.5.1.7 Molten Salt. The molten salt system handles a "mashed" or shredded feed (feed configuration h). The molten salt unit contains a bed of molten salt, which is maintained as a froth by the flue gas

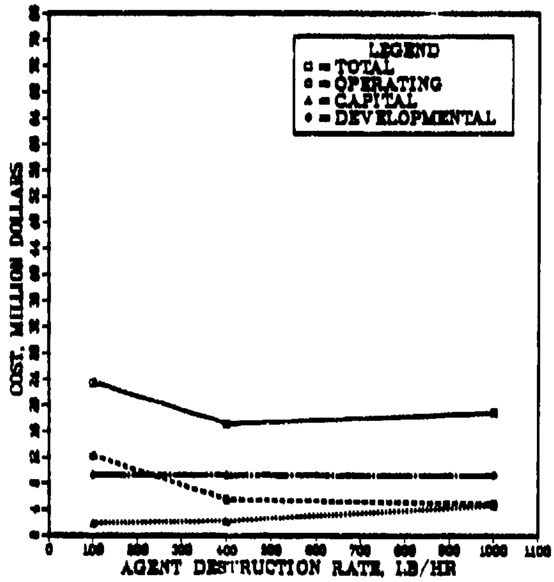



FIGURE 19. VACUUM FURNACE CONCEPT
Life Cycle Cost Curves
Single Site, Feedstock c

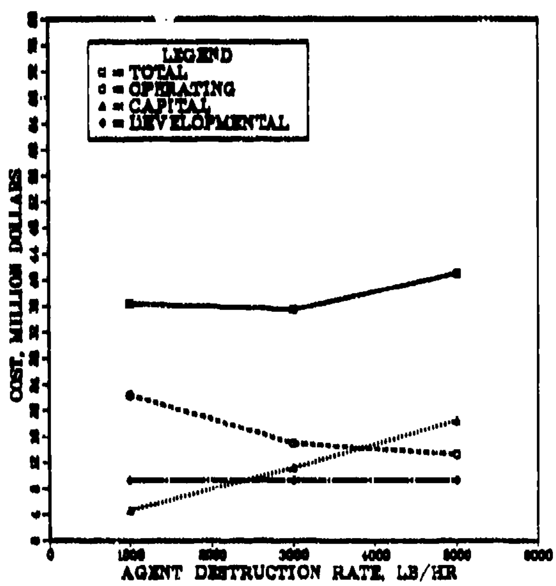



FIGURE 20. VACUUM FURNACE CONCEPT
Life Cycle Cost Curves
Collocated Site, Feedstock c

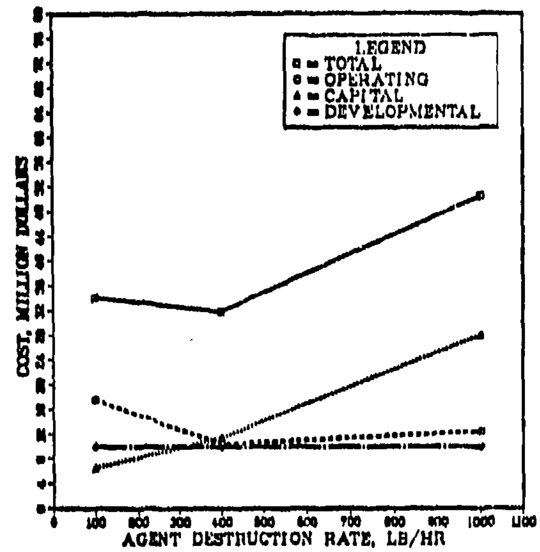



FIGURE 21. SHAFT FURNACE CONCEPT
Life Cycle Cost Curves
Single Site, Feedstock b

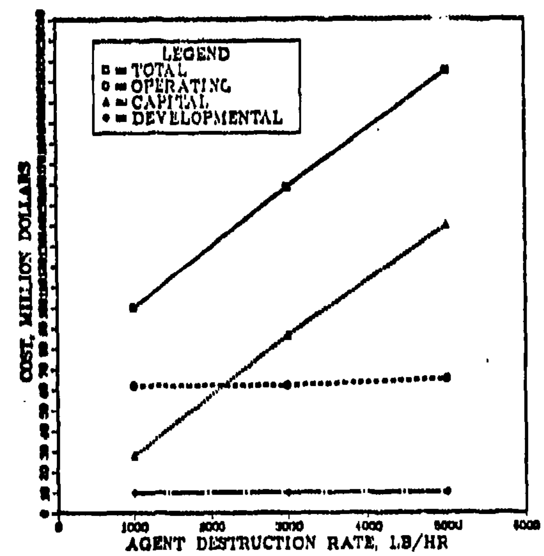



FIGURE 22. SHAFT FURNACE CONCEPT
Life Cycle Cost Curves
Collocated Site, Feedstock b

the flue gas stream, over a pool of molten metal. In concept, noxious gases are removed by the molten salt, however, it is likely that a downstream scrubbing system will be required to provide redundancy.

Knowledge gaps center around the fate of phosphorus and materials compatibility.

Total life cycle costs range from $18.4 million to $22.8 million for single site and from $45.4 million to $77.9 million for collocated site. Life cycle costs are presented in Figures 23 and 24. This concept was eliminated from further consideration.

A detailed engineering and economic analysis on the molten salt process will be found in Appendix J.

2.5.1.8 Underground Detonation. The underground detonation concept is a collocated operation designed to destroy the entire lethal agent inventory with one underground detonation. The applicable feed stock is configuration a.

This approach requires no mechanical preparation, no flue gas cleanup, and provdies the most effective ultimate disposal scenario. However it would be a politically sensitive approach. Furthermore, testing would be extremely difficult. This concept was eliminated from further consideration.

It is estimated that total life cycle costs would exceed $393 million.

Details on the underground detonation engineering and economic analysis will be found in Appendix K.

### 2.5.2 Design Plan

A Design Plan was prepared outlining laboratory studies on the four most promising concepts:

Acid Roaster
Rotary Kiln
Molten Metal

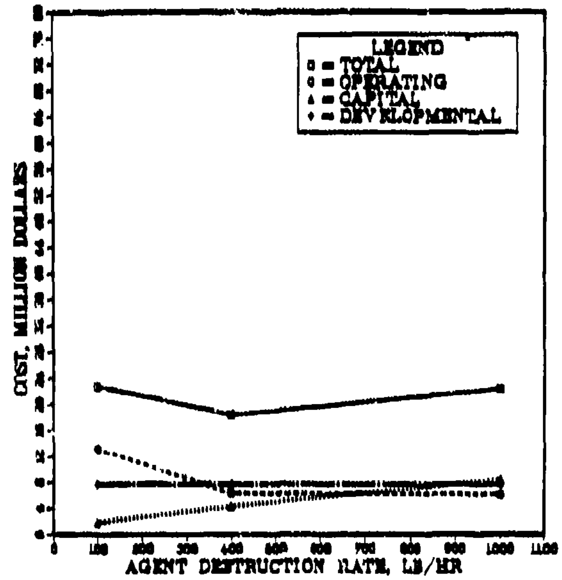



FIGURE 23. MOLTEN SALT CONCEPT
Life Cycle Cost Curves
Single Site, Feedstock g/h

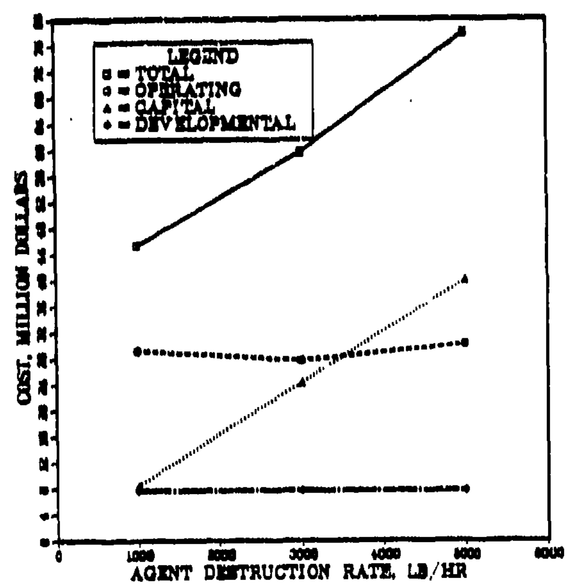



FIGURE 24. MOLTEN SALT CONCEPT
Life Cycle Cost Curves
Collocated Site, Feedstock g/h

Fluidized-Bed.

These four concepts were selected based on an overall consideration of the engineering and economic evaluations and are believe to offer the greatest potential for efficient demiliarization of the chemical agent munitions stockpile. The technical approach to be used to develop these concepts can be found in the Design Plan issued January 31, 1983.

## 3.0 CONCLUSIONS

A large number of thermal processes for destruction of hazardous and toxic materials are developed or are under development in industry. Many of these processes could be applied to the destruction of chemical agents with little or no additional development. But when the destruction of chemical agents is coupled with the problems inherent in handling and rendering safe munitions containing fuses, bursters, and propellants, the selection of appropriate processes becomes much more difficult and limited.

Of 44 thermal processes identified in this study, 4 appear to have sufficient promise to be considered for further development in the laboratory. These processes are:

1. Acid Roaster. A process in which separate whole munitions are eroded in an acid bath to free the chemical agents and energetic materials. The resultant slurry is roasted to destroy the agent and energetic materials and to recover acid gases which are recycled to the acid bath.
2. Rotary Kiln. A process which uses a rotary kiln to incinerate feeds ranging from whole punctured munitions to cut munitions.
3. Molten Metal. A process which pyrolizes and incinerates agents and energetic materials yielding a molten metal and fused salt product. This process accepts punctured whole munitions or munitions cut into pieces.
4. Fluidized-Bed. A process in which punctured whole munitions or munitions cut into pieces are incinerated in a fluidized-bed.

These processes have moderate to low technical risk, are at or near state-of-the-art technology, and have the potential of offering economic advantages when coupled with the required mechanical preparation.

## 4.0 RECOMMENDATIONS

It is recommended that one or more of the following processes be developed further in the laboratory to identify the more viable processes and to obtain design information necessary for further development at a pilot scale. The processes, in order of present economic and engineering preference, are:

1. Acid Roaster
2. Rotary Kiln
3. Molten Metal
4. Fluidized-Bed

Detailed recommendations for the laboratory study are given in the Design Plan issued January 31, 1983.

## APPENDIX A

## BIBLIOGRAPHY OF PERTINENT LITERATURE REFERENCES

# APPENDIX A

## BIBLIOGRAPHY OF PERTINENT LITERATURE REFERENCES

This bibliography is organized by type of document and accession number for quick retrieval of the document. The type of document is specified by B for book, R for report, J for journal article, PP for published paper, P for patents, ML for manufacturers' literature, and M for microfiche. Also included with each bibliographic listing are the thermal technologies that the document covers and if the document is not part of the project files, the individual at Battelle who has the document.

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Battelle Circulation: Bert O'Connell

Technologies

Multiple Hearth, Fluidized Bed
Liquid Injection, Fume Incinerator, Rotary Kiln, Multiple Chamber, Cyclonic, Auger Combustor
Ship-Mounted, Catalytic, Oxygen, Pyrolysis, Calcination, Boilers, Wet-Air Oxidation, Distillation, Evaporation
Molten Salt, Plasma Arc
Microwave Discharge

B-2

Sittig, Marshall, Incineration of Industrial Hazardous Wastes and Sludges. Noyes Data Corporation. Park Ridge, New Jersey (1979).

Battelle Circulation: Bruce Rising

Technologies

Afterburners, Catalytic Incinerators, Cyclon Furnaces, Direct-Flame Thermal Incinerators, Electric Furnaces, Flares, Fluidized Beds, Liquid Waste Combustors, Molten Salt, Multip Chamber, Multiple Hearth, Open Burning, Pebb Bed Incinerators, Rotary Kiln, Seagoing, Wet Air Oxidation Units.

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| R-9 | Bell, B. A., and Whitmore, F. C. Kepone Incineration Test Program, EPA-600/2-78-108. U.S. EPA Office of Research and Development, Municipal Environmental Research Laboratory, Cincinnati, Ohio (May 1978).<br><br>Property of Ted Prociv<br><br>Technologies<br><br>Rotary Kiln (Pyrolyzer), Incinerator (Afterburner) |

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| R-10 | Edwards, Barbara, Ph.D. "Fluidized Bed Combustion of Hazardous Waste", Draft. Prepared by Ebon Research Systems for U.S. EPA Municipal Environmental Research Laboratory, Cincinnati, Ohio (March 1980).<br><br>Technologies<br><br>Fluidized Bed |
| R-11 | Castaldini, C., et al. "A Technical Overview of the Concept of Disposing of Hazardous Wastes in Industrial Boilers", Draft. Prepared by Acurex Corporation for U.S. EPA Industrial Environmental Research Laboratory, Cincinnati, Ohio (January 1981).<br><br>Technologies<br><br>Industrial Boilers |
| R-12 | U.S. EPA Industrial Environmental Research Laboratory. "Proceedings of the Hazardous Waste Combustion Workshop", Draft, Cincinnati, Ohio (April 1981) Prepared by Battelle Memorial Institute (November 1981).<br><br>Technologies<br><br>Industrial Boilers |

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| R-13 | Yosim, S. J., Kellog, L. G., and Sudar, S. "Molten Salt Destruction of HCB and Chlordane", Draft. Prepared by Rockwell International Energy Systems Group for U.S. EPA Office of Research and Development, Industrial Environmental Research Laboratory, Cincinnati, Ohio (n.d.). |
| | Technologies |
| | Molten Salt |
| R-14 | "Environmental Assessment for a Program to Demonstrate the Use of Recycled Fuels in Cement Plants". Prepared by the San Juan Cement Co. for U.S. EPA Industrial Environmental Research Laboratory, Cincinnati, Ohio (November 1980). |
| | Technologies |
| | Cement Kiln |
| R-15 | Bennett, R. W., et al. "A Study of Equipment, Processes, and Systems for a Demilitarization Facility". Prepared by Battelle Memorial Institute for Naval Facilities Engineering Command, Western Division (January 31, 1975). |
| | Property of Bert Weller |
| | Technologies |
| | Rotary Kiln |
| | Other |
| | Munitions and Explosives Preparation Technologies |

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| R-16 | Brazhnikov, V. I., et al. Furnace for Thermal Treatment of Liquid Industrial Waste Waters Containing Toxic Organic Impurities. Army Foreign Science and Technology Center, Charlottesville, Virginia; NTIS AD-783 850 (September 6, 1972).<br><br>Technologies<br><br>Liquid Injection/Vertical Shaft |
| R-17 | Shapira, N. I., et al. State-of-the-Art Study: Demilitarization of Conventional Munitions, EPA-600/2-78-012. Prepared by American Defense Preparedness Association for U.S. EPA Office of Research and Development, Industrial Environmental Research Laboratory, Cincinnati, Ohio (February 1978).<br><br>Property of Ted Prociv<br><br>Technologies<br><br>Rotary Kiln, Wet Air Oxidation, Fluidized Bed, Closed Pit Incinerator, Batch Box Incinerator, Microwave, Air Curtain Incinerator<br><br>Other<br><br>Munitions Preparation Technologies |
| R-18 | Leary, J. F. Ultimate Disposal of Oil and Hazardous Materials, CG-D-36-76. Prepared for United States Coast Guard Department of Transportation, Washington, D.C.; NTIS, Springfield, Virginia, AD-A035 137 (October 1975).<br><br>Technologies<br><br>Municipal Incinerators, Portable Incinerators, Ship-Mounted Incinerators |

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| R-19 | Lawless, E. W., Ferguson, T. L., and Meiners, A. F. Guidelines for the Disposal of Small Quantities of Unused Pesticides, EPA-670/2-75-057. Prepared by Midwest Research Institute for U.S. EPA Office of Research and Development, National Environmental Research Center, Cincinnati, Ohio; NTIS, Springfield, Virginia, PB-244-557 (June 1975).<br><br>Property of Ted Prociv<br><br>Technologies<br><br>Small-Scale Pesticide Disposal Techniques |
| R-20 | Rosen, H. H. Pesticide Pyrolysis Device. Army Land Warfare Laboratory, Aberdeen Proving Ground, Maryland (June 1974); NTIS AD-784 553, Springfield, Virginia.<br><br>TACTEC<br><br>Technologies<br><br>Pyrolyzer |
| R-21 | Bucci, R. J., and Meseke, E. L. Process Description and Compendium of Chemical Agent Identification Sets Disposal Program Studies and Reports, ARCSL-SP-81018. Chemical Systems Laboratory, Aberdeen Proving Ground, Maryland (November 1981).<br><br>TACTEC<br><br>Technologies<br><br>Molten Salt, Rotary Kiln, Rocky Mountain Arsenal Facilities |

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| R-22 | Stearns-Roger Incorporated. Final Process Design of the Agent Destruction System for CAMDS. Prepared for Edgewood Arsenal, Aberdeen Proving Ground, Maryland; Defense Technical Information Center, Alexandria, Virginia (February 1977).<br><br>TACTEC<br><br>Technology<br><br>Chemical Neutralization Process<br><br>Other<br><br>Agent Detoxification Processes |
| R-23 | Chem Demilitarization Install Restoration. "Demilitarization Plan Operation of the Chemical Agents Munition Disposal System (CAMDS)". Aberdeen Proving Ground, Maryland (March 1977).<br><br>TACTEC<br><br>Technologies<br><br>Deactivation Furnace, Metal Parts Furnace, Dunnage Incinerator<br><br>Other<br><br>Munitions Preparation Systems |

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| R-24 | Meseke, E. L., and Herd, R. E. Small-Scale Pilot Incineration Feasibility Study of Chemical Identification Sets, ARCSL-TR-78069. Chemical Systems Laboratory, Aberdeen Proving Ground, Maryland (May 1979).<br><br>TACTEC<br><br>Technologies<br><br>Liquid Injection |
| R-25 | Brankowitz, R. W. Demilitarization of Mustard Agent (HD) at Fort McClellan, Alabama, ARCSL-TR-77051. Chemical Systems Laboratory, Aberdeen Proving Ground, Maryland (April 1978).<br><br>TACTEC<br><br>Technologies<br><br>Chemical Neutralization |
| R-26 | Scott, J., et al. Engineering Study of the Incineration Facilities at Rocky Mountain Arsenal. Department of the Army, Edgewood Arsenal, Aberdeen Proving Ground, Maryland; Defense Technical Information Center, Alexandria, Virginia (February 1977).<br><br>TACTEC<br><br>Technologies<br><br>Processes Used at Rocky Mountain Arsenal |

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| R-27 | Midland-Ross Corporation, Surface Combustion Division. Final Concept Design Report Deactivation Furnace, DRCPM-DRD-CR-74042. Chemical Demilitarization and Installation Restoration, Aberdeen Proving Ground, Maryland; Defense Technical Information Center, Alexandria, Virginia (November 1974).<br><br>TACTEC<br><br>Technologies<br><br>Continuous Processing Rotary Retort Furnace |
| R-28 | Valis, R. J., and Vigus, E. S. Pyrolysis of Detoxified Agent Wastes II, ARCSL-TR-77024. Chemical Systems Laboratory, Aberdeen Proving Ground, Maryland (September 1977).<br><br>TACTEC<br><br>Technologies<br><br>Experimental Pyrolysis Equipment |
| R-29 | Santos, J., et al. Design Guide for Propellant and Explosive Waste Incineration. U.S. Army, Picatinny Arsenal, Dover, New Jersey (October 1973).<br><br>TACTEC<br><br>Technologies<br><br>Rotary Kiln, Vertical Induced Draft, Fluid Bed |

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| R-30 | Cheselske, F. J., et al. Study of Catalytic and Thermal Decomposition of Toxic Agents. Department of the Army, Edgewood Arsenal, Maryland (October 1970).<br><br>TACTEC<br><br>Other<br><br>Kinetic Studies |
| R-31 | Sass, S., and Davis, P. M. Laboratories Studies on the Incineration of Mustard (HD), EATR 4516. Department of the Army, Edgewood Arsenal, Maryland (May 1971).<br><br>Other<br><br>Mustard Destruction Efficiency |
| R-32 | Pugh, D. L., et al. Incineration of GB and Containment of Gaseous Products, EATR 4463. Department of the Army, Edgewood Arsenal, Maryland (October 1970).<br><br>Other<br><br>GB Destruction Efficiency |

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| R-33 | Hildebrandt, H. F., Gervasoni, T. R., and Baker, J. A. Incineration of VX and Containment of Gaseous Products (U), EATR 4586. Department of the Army, Edgewood Arsenal, Maryland (March 1972).<br><br>Other<br><br>VX Destruction Efficiency |
| R-34 | Molten Salt Coal Gasification Process Development, Phase 1 Final Report, PDU Operations, DOE/ET/10296-66. Prepared by Rockwell International Environmental and Energy Systems Division for U.S. Department of Energy (May 1980).<br><br>Technologies<br><br>Molten Salt Gasification |
| R-35 | Molten Salt Coal Gasification Process Development Unit, Phase 1 Final Report, Commercial Plant Study, DOE/ET/10296-66. Prepared by Rockwell International for the U.S. Department of Energy (May 1980).<br><br>Technologies<br><br>Molten Salt |

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| R-36 | Reeves, A. M., and Kurtz, M. C. "Thermal Decomposition of GB". Prepared by Army Chemical Center, Chemical and Radiological Laboratories (August 31, 1954).<br><br>Other<br><br>Agent Chemistry |
| R-37 | Lapp, R. R., and Schneider, C. J. "An Investigation of the Thermal Decomposition of BIS (2,ethyl hexyl) Hydrogen Phosphite and Agent VX as Vapor at Elevated Temperatures". Cornell Aeronautical Laboratory, Inc. (May 31, 1962).<br><br>Other<br><br>Agent Chemistry |
| R-38 | Runnion, K. N., and Wagner, Arnold. Incineration of VX and GB with Emphasis on Phosphoric Acid Mist Removal, EM-TR-75037. Department of the Army, Edgewood Arsenal, Aberdeen Proving Ground, Maryland (April 1975).<br><br>Technologies<br><br>Liquid Injection |
| R-39 | Data from Mustard Disposal Operation (Project Eagle) at Rocky Mountain Arsenal (1972-1974). Provided by Mike Asselin. |

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| R-40 | Fradkin, L., and Barisas, S. Technologies for Treatment, Reuse, and Disposal of Polychlorinated Biphenyl Wastes, ANL/EES-TM-168. Argonne National Laboratory, Argonne, Illinois (January 1982).<br><br>Technologies<br><br>Rotary Kiln, Liquid Injection, Multiple Hearth, Fluidized Bed Multiple Chamber, Catalytic Combustion, Pyrolysis, Starved-Air Combustion, Molten Salt, Catalytic Afterburner, Mobile Incinerator, Controlled-Air Incinerator, Molten Iron, Diesel Engine, Incineration at Sea, High-Efficiency Boilers, Plasma-Arc, Catalyzed Wet Oxidation, Hydrothermal Dechlorination |
| R-41 | Muralidhara, H. S., and Young, J. B. "Comparative Evaluation of Sumitomo Metals Coal Gasification Process". Report for Sumitomo Metal Industries Ltd. prepared by Battelle Columbus Laboratories (November 1981).<br><br>Technology<br><br>Molten Metal/Steel Furnace |
| R-42 | Howes, J. E., O'Connell, W. L., and Riggin, R. M. "Measurement of Emissions from Burning PCBs in the Mobile Waste Processor". Report for Pyrotech Systems, Inc., prepared by Battelle Columbus Laboratories, Columbus, Ohio (May 6, 1982).<br><br>Technology<br><br>Mobile Liquid Injection/High-Temperature Oxygen Incineration |

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| R-43 | Schorr, J. Richard, et al. "Breakthrough Tcchnologies". Report to Mitsubishi Research Institute from Battelle Columbus Laboratories, Columbus, Ohio (January 1982).<br><br>Technologies<br><br>Nuclear Fusion, Geothermal |

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| J-1 | Hitchcock, D. A. "Solid-Waste Disposal: Incineration". Chemical Engineering (May 21, 1979) pp. 185-194.<br><br>Technologies<br><br>Pyrolysis, Multiple Hearth, Fluidized Bed, Liquid Incinerator, Gas Incinerator, Rotary Kiln, Wet-Air Oxidation, Molten Salt, Multiple Chamber, Ship-Mounted Incinerators |
| J-2 | Ross, R. D. "Burn, Hazardous Waste Burn". ChemTech (November, 1980) pp. 708-712.<br><br>Technologies<br><br>Conventional Forced Draft Burner, Cyclonic Incinerator, Rotary Kiln, Fluidized Bed, Multiple Hearth, Catalytic. |
| J-3 | Pojasek, R. B. "Disposing of Hazardous Chemical Wastes". Environmental Science and Technology, Vol. 13, No. 7 (July 1979) pp. 810-814.<br><br>Technologies<br><br>Molten Salt, Ocean Incineration |
| J-4 | Fish, R. A. "Disposal Methods for Hazardous Wastes". Journal of Oil Col. Chem. Assoc., Vol. 60, No. 8 (1977) pp. 296-299.<br><br>Technologies<br><br>Rotary Kiln, Ocean Incineration |
| J-5 | Berry, E. E. and MacDonald, L. P., "Experimental Burning of Used Automotive Crankcase Oil in a Dry-Process Cement Kiln". Journal of Hazardous Materials, Vol. 1 (1975/1976) pp. 137-156.<br><br>Technology<br><br>Cement Kiln |

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| J-6 | Tenzer, R. et. al. "Characteristics of the Mobile Field Use System for the Detoxification/Incineration of Residuals from Oil and Hazardous Material Spill Clean-Up Operations". Journal of Hazardous Materials, Vol. 3 (1979) pp. 61-75.<br><br>Technology<br><br>Mobile Rotary Kiln |
| J-7 | "EPA-Funded PCB Test Burns are Likely Success". Chemical and Engineering News, (July 19, 1982) pp. 29-30.<br><br>Technology<br><br>Two-Chamber, controlled Air Incinerator (conventional) |
| J-8 | Basta, Nicholas. "Firms Avidly Seek New Hazardous Waste Treatment Process". Chemical Engineering, Vol. 89, No. 18 (September 6, 1982) pp. 53-57.<br><br>Technologies<br><br>Mobile Rotary Kiln, Wet-Air Oxidation, Supercritical Fluid |
| J-9 | Yasui, Takaji and Matsuoka, Kyoshi. "Hydrothermal Decomposition of Polychlorinated Biphenyls". Environmental Science and Technology (1980) pp. 550-552.<br><br>Technology<br><br>Hydrothermal |

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| J-10 | Modell, Michael, et al. "Supercritical Water". Solid Waste Management, Vol. 25, No. 8 (August 1982) pp. 26-76.<br><br>Technology<br><br>Supercritical Fluids |
| J-11 | "Using Supercritical Water to Destroy Tough Wastes". Chemical Week, Vol. 130, No. 16 (April 21, 1982) p. 26.<br><br>Technology<br><br>Supercritical Fluid |
| J-12 | Flachseberg, Paul. "German Lime Kiln Developments Meet Quality Demands". Rock Products (July 1970) pp. 75-83.<br><br>Technologies<br><br>Cross-Flow Kilns, Double-Inclined Kiln, Annual Shaft Kiln, Rotary Kiln |
| J-13 | Gribbin, Walter. "Vertical Shaft Kilns--Present and Future". Rock Products (December 1970) pp. 68-70.<br><br>Technology<br><br>Vertical-Shaft Kiln |

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| PP-1 | Baillod, R. C. et al. "Wet Oxidation of Toxic Organic Substances". Proceedings of the Industrial Waste Conference, 34th; Ann Arbor Science Publishers, Ann Arbor, Michigan (1980), pp. 206-213.<br><br>Technology<br><br>Wet-Air Oxidation |
| PP-2 | Johnson, J. G. et al. "Destruction of Hazardous Wastes by the Molten Salt Destruction Process". Paper presented at the Environmental Protection Agency Seminar, Ft. Mitchell, Kentucky (March 1982).<br><br>Technology<br><br>Molten Salt |
| PP-3 | Yosim, S. J. et al. "Destruction of Hazardous Wastes by Molten Salt Combustion". Toxic and Hazardous Waste Disposal, Volume 4; Ann Arbor Science Publishers, Inc., Ann Arbor, Michigan (1979), pp. 227-243.<br><br>Technology<br><br>Molten Salt |

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| PP-4 | Kenson, R. E. et al. "Development of Effective Incineration Processes for Toxic Organic Air Pollutants". Paper presented at the 70th Annual Meeting of the Air Pollution Control Association, Toronto, Ontario, Canada (June 1977).<br><br>Other<br><br>Incineration Operating Variables |
| PP-5 | Hemsath, Dr. K. H., and Schultz, T. J. "Application of Advanced Combustion Technology for the Disposal of Toxic Waste". Prepared by Midland-Ross Corporation, Surface Division for presentation at the Wastern States Combustion Institute's Spring Meeting, Seattle Washington (April 1977).<br><br>Technologies<br><br>Midland-Ross' Explosives and Metal Parts Furnaces.<br>Midland-Ross' Kepone Incineration Equipment.<br>Rotary Kiln, Roller Hearth Furnace |
| PP-6 | Barton, T. G., and Arsenault, G. P. "Toxic Waste Destruction by Plasma Pyrolysis". Proceedings of the 36th Industrial Waste Conference; Ann Arbor Science Publishers, Ann Arbor, Michigan (1982), pp. 177-183.<br><br>Technology<br><br>Plasma Pyrolysis |

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| PP-7 | Hornig, A. W. "Decomposition of Chlorinated Hydrocarbons Using a Novel High-Temperature Fluid Wall Reactor". Proceedings of the 36th Industrial Waste Conference; Ann Arbor Science Publishers, Ann Arbor, Michigan (1982), pp. 177-183.<br><br>Technology<br><br>High-Temperature Fluid Wall |
| PP-8 | Freeman, H. M. "Review of Selective Innovative Thermal Hazardous Waste Destruction Processes". Paper to be presented at the American Institute of Chemical Engineers Conference, Cleveland, Ohio (September 1982).<br><br>Technologies<br><br>Fluidized Bed, High-Temperature Fluid Wall, Molten Salt, Cement Kiln, Mobile High-Temperature Incineration, Pyrolytic Incineration, Wet Air Oxidation |
| PP-9 | Frankel, I., Sanders, N., Vogel, G. "Profile of the Hazardous Waste Incinerator Manufacturing Industry". Paper for presentation at the American Institute of Chemical Engineers Conference, Cleveland, Ohio (September 1982).<br><br>Technologies<br><br>Fixed Hearth, Liquid Injection Rotary Kiln, Fluidized Bed, Induction Heating, Pulse Hearth Reciprocating Grate, Infrared Heating |

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| PP-10 | Baur, J. M., and Iwata, H. "Development of Slagging Coal Combustors for MHD Applications". TRW Systems and Energy Group, Redondo Beach, California (n.d.).<br><br>Technology<br><br>Rocket Combustor Injector/Magnetohydrodynamic Power Generation |
| PP-11 | Cook, C. S., et al. "A Regeneratively Air Cooled Cyclone Coal Combustor for Utility Boiler Application". General Electric Company, Space Sciences Laboratory, King of Prussia, Pennsylvania (n.d.).<br><br>Technology<br><br>Cyclone Coal Combustor |
| PP-12 | Rinker, T. L. "Regional Facilities for Hazardous Waste Disposal". The American Society of Mechanical Engineers, New York, New York (July 23, 1980).<br><br>Technologies<br><br>Fluidized Bed, Rotary Kiln |

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| P-1 | Greenberg, Jacob, "Method of Catalytically Inducing Oxidation of Carbonaceous Materials by the Use of Molten Salts", U.S. Patent 3,647,358 (July 23, 1970).<br><br>Technology<br><br>Molten Salt |
| P-2 | Eck, J. C., "Furnace for Combined Incineration of Rubbish, Garbage, and Sewage Sludge", U.S. Patent 3,777,680 (December 11, 1973).<br><br>Technology<br><br>Multiple Hearth |
| P-3 | Porter, S. M., Weiner, E. C., Shielder, H. W., "Solid Waste Disposal Method and Apparatus", U.S. Patent 3,716,002 (February 13, 1973).<br><br>Technology<br><br>Rotary Kiln |
| P-4 | Roberts, E. J., "Fluid Bed Incineration of Chloride Containing Waste Streams", U.S. Patent 3,864,458 (February 4, 1975).<br><br>Technology<br><br>Fluid Bed |
| P-5 | Saitoh, Shigeru, et. al., "Moving Bottom Incinerator", U.S. Patent 3,861,331 (January 21, 1975).<br><br>Technology<br><br>Moving Bottom |

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| P-6 | Yosim, S. J., "Non-Polluting Disposal of Explosives and Propellants", U.S. Patent 3,778,320 (December 11, 1973).<br><br>Technology<br><br>Molten Salt |
| P-7 | Sharpe, P. S., "Thermal Oxidation of Wastes and Apparatus Therefor", U.S. Patent 3,892,190 (July 1, 1975).<br><br>Technology<br><br>Liquid Injection |
| P-8 | Tsurata, H., Makiguchi, M., "Rotary Kiln Type-Solid Waste Incinerating System and Method", U.S. Patent 3,827,379 (August 6, 1974).<br><br>Technology<br><br>Rotary Kiln |
| P-9 | Sargent, E. A., Doner, A. J., "Apparatus for Disposing of Solid Wastes", U.S. Patent 3,842,762 (October 22, 1974).<br><br>Technology<br><br>Rotary Kiln |
| P-10 | Yosim, S. J., et. al., "Disposal of Organic Pesticides", U.S. Patent 3,845,190 (October 29, 1974).<br><br>Technology<br><br>Molten Salt |

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| P-11 | Bolejack, W. J., Jr., Daniel, T. K., Rolison, D. E., "Incineration Process for Disposal of Waste Propellant and Explosives", U.S. Patent 3,848,548 (November 19, 1974).<br><br>Technology<br><br>Rotary Kiln |
| P-12 | Santoleri, J. J., "Incinerator for Aqueous Waste Material", U.S. Patent 3,861,330 (January 21, 1975).<br><br>Technology<br><br>Liquid Injection |
| P-13 | Monroe, E. S., Jr., "Cyclonic Incinerator", U.S. Patent 3,865,054 (February 11, 1975).<br><br>Technology<br><br>Cyclonic Incinerator |
| P-14 | Gunn, N. I., "Electric Incinerator", U.S. Patent 3,877,399 (April 15, 1975).<br><br>Technology<br><br>Electric Furnace |
| P-15 | Kishigami, K., Koybayashi, H., Oshima, S., "Incineration Method for Combustible Industrial Wastage and a Fluidized Bed Furnace Used Therefor", U.S. Patent 3,888,193 (June 10, 1975).<br><br>Technology<br><br>Fluidized Bed |

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| P-16 | Albrecht, E., et.al., "Fluidized Bed Furnace Having Coarse Particle Discharging Device", U.S. Patent 3,910,208 (October 7, 1975).<br><br>Technology<br><br>Fluidized Bed |
| P-17 | Roberts, E. J., Angevine, A., "Fluid Bed Incineration of Wastes Containing Alkali Metal Chlorides", U.S. Patent 3,907,674 (September 23, 1975).<br><br>Technology<br><br>Fluidized Bed |
| P-18 | Zetterström, K. A., "Device for the Purification of Process Wastes Gases", U.S. Patent 3,940,253 (February 24, 1976).<br><br>Technology<br><br>Pollution Control |
| P-19 | Copeland, G. C., "Method for Oxidation of Sulfur-Containing Substances", U.S. Patent 3,949,684 (April 13, 1976).<br><br>Technology<br><br>Fluidized Bed |
| P-20 | Bernaliner, M. N., et. al., "Process and Cyclone Reactor for Fine Decontamination of Industrial Waste Water Containing Organic and Refractory Mineral Impurities", U.S. Patent 3,974,021 (August 10, 1976).<br><br>Technology<br><br>Cyclonic Incinerator |

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| P-21 | Greenberg, Jacob, "Solid-Liquid Waste Incinerator Utilizing Liquid Catalysts", U.S. Patent 3,974,784 (August 17, 1976).<br><br>Technology<br><br>Liquid Injection (Submerged Flame) |
| P-22 | Priestely, R. J., "Dilute Phase Waste Incinerator", U.S. Patent 4,021,184 (May 3, 1977).<br><br>Technology<br><br>Fluidized Bed |
| P-23 | Barry, L. T., Czope, G. W., "Method and Apparatus for Treating Waste Material in a Counter-Current Incinerator", U.S. Patent 4,046,085 (September 6, 1977).<br><br>Technology<br><br>Multiple Hearth |
| P-24 | Dreasche, C. F., Jr., "Method and Apparatus for Incinerating Waste Material", U.S. Patent 4,050,389 (September 27, 1977).<br><br>Technology<br><br>Multiple Hearth |
| P-25 | Hara, S., Kato, T., "Method of Treating Sewage Sludge", U.S. Patent 4,050,390 (September 27, 1977).<br><br>Technology<br><br>Multiple Hearth |

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| P-26 | Miller, S. T., Hardison, W. G., "Catalytic Abatement System", U.S. Patent 4,054,418 (October 18, 1977).<br><br>Technology<br><br>Pollution Control |
| P-27 | Sowards, N. K., "Low Pollution of Solid Waste", U.S. Patent 4,075,953 (February 28, 1978).<br><br>Technology<br><br>Fluidized Bed (combined with cyclonic) |
| P-28 | Kershner, Seymour, "Fibrous Filter Incinerator", U.S. Patent 4,085,689 (April 25, 1978).<br><br>Technology<br><br>Filter Incinerator |
| P-29 | Lanier, John H. Jr., "High Temperature Oxygen Hazardous Waste Incinerator", U.S. Patent 4,338,870 (July 13, 1982).<br><br>Technology<br><br>Liquid Injection (injection into preheated oxygen chamber) |
| P-30 | Hoskinson, Gordon H., "Combustion Apparatus Utilizing an Auger Having an Integral Air Supply System", U.S. Patent 4,338,869 (July 13, 1982).<br><br>Technology<br><br>Auger Combustor |

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| P-31 | Lientz, la Clede, "Refuse Burning Process and Apparatus", U.S. Patent 4,338,868 (July 13, 1982).<br><br>Technology<br><br>Rotary Furnace |
| P-32 | Moore, Walter T., "Solar Powered Chemical Processing Method and Apparatus", U.S. Patent 4,339,922 (July 13, 1982).<br><br>Technology<br><br>Solar Powered Chemical Processing Method and Apparatus |
| P-33 | Van Loar, Jacobus, Felthuis, Jacob, and Kastelic, Wilhemus, "Shaft Furnace Having Cooling Plates", U.S. Patent 4,332,554 (June 1, 1982).<br><br>Technology<br><br>Shaft Furnace |
| P-34 | Fitch, R. E. and Tyer, C., "Fuel Feed Technique for Auger Combustor", U.S. Patent 4,331,084 (May 25, 1982).<br><br>Technology<br><br>Auger Combustor |
| P-35 | Gold, Louis, "Management of Chemical Toxic Waste", U.S. Patent 4,331,088 (May 25, 1982).<br><br>Technology<br><br>Coal Reactor (vertical shaft furnace) |

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| P-36 | Kranzl, Franz A., and Springer, Helmut, "Walking Beam Furnace", U.S. Patent 4,330,262 (May 18, 1982).<br><br>Technology<br><br>Walking Beam |
| P-37 | Burton, Robert E., "Burning System and Method", U.S. Patent 4,329,931 (May 18, 1982).<br><br>Technology<br><br>Elongated Chamber - Hydraulic Ram |
| P-38 | Hughes, David E., "Melting Glass with Reduced $NO_x$ Emissions", U.S. Patent 4,328,020 (May 4, 1982).<br><br>Technology<br><br>Glass Melting Furnace |

| ACCESSION NUMBER | REFERENCE |
| --- | --- |
| ML-1 | Summary of the University of Tennessee's Magnetohydrodynamic Process for the Generation of Electricity.<br><br>Technology<br><br>Magnetohydrodynamic |
| ML-2 | Summary of the Commenwealth Scientific and Industrial Research Organization's Fluidized Bed Combustor for Coal Washery Wastes.<br><br>Technology<br><br>Fluidized Bed |
| ML-3 | Summary of Battelle's Spouted Bed Combustor<br><br>Technology<br><br>Spouted Bed |
| ML-4 | Summary of Energy Concepts Company's Fuel Gas Cleaning Process.<br><br>Technology<br><br>Molten Salt |
| ML-5 | Trip Report: Review of Sumitomo Metals Cretive Gas and Steel Coal Gasification Process. Prepared by Battelle Coal Utilization Technologies Study Group (June 1, 1982).<br><br>Technology<br><br>Molten Metal (Iron) |
| ML-6 | "Process Description for the Thermal Destruction of Toxic Waste Materials". Proposal prepared by the Franklin Research Center, Process Technology Division for Battelle Memorial Institute (July 21, 1982).<br><br>Technology<br><br>Rotary Kiln |

| ACCESSION NUMBER | REFERENCE |
|---|---|
| ML-7 | Solar Zapper Process Description. Prepared by Focus Environmental Services (September 1981).<br><br>Technology<br><br>Solar |
| ML-8 | Description of High-Temperature Fluid-Wall Reactor. Thagard Research Corporation, Irvine, California (n.d.).<br><br>Technology<br><br>High-Temperature Fluid Wall |

| ACCESSION NUMBER | REFERENCE |
|---|---|
| M-1 | Wilkinson, R. R., Kelso, G. R., and Hopkins, F. C. State-of-the-Art Report: Pesticide Disposal Research, EPA-600/2-78-183. Prepared by Midwest Research Institute for U.S. EPA Office of Research and Development, Municipal Environmental Research Laboratory, Cincinnati, Ohio; NTIS PB 284 716 (September 1978).<br><br>Microfiche of report |
| M-2 | Scurlock, A. C. Incineration in Hazardous Waste Management, EPA/530/SW-141. U.S. EPA Office of Solid Waste Management Programs, Washington, D.C.; NTIS PB 261 049 (1975).<br><br>Technology<br><br>Rotary Kiln, Multiple Hearth, Liquid Injection, Fluidized Bed, Molten Salt, Wet-Oxidation, Plasma Destruction, Multiple Chamber Gas Combustion, Pyrolysis |
| M-3 | Gruber, G. I. Assessment of Industrial Hazardous Waste Practices, Organic Chemicals, Pesticides and Explosives Industries. Prepared by TRW Systems Group for U.S. EPA Office of Solid Waste Management Programs, Washington, D.C.; NTIS PB 251 307 (April 1975).<br><br>Technology<br><br>Rotary Kiln, Fluidized Bed, Liquid Injection<br><br>Other<br><br>Treatment and disposal technologies employed in the military explosives industry |

| ACCESSION NUMBER | REFERENCE |
|---|---|
| M-4 | Ottinger, R. S., et al. Recommended Methods of Reduction, Neutralization, Recovery or Disposal of Hazardous Waste, Volume III, EPA-670/2-73-053-C. Prepared by TRW Systems Group for U.S. EPA National Environmental Research Center, Cincinnati, Ohio; NTIS PB 224 582 (August 1973).<br><br>Technology<br><br>Fluidized Bed, Catalytic Incineration, Rotary Kiln, Liquid Injection, Open-Pit, Open Incineration, Multiple Chamber, Multiple Hearth, Flares<br><br>Other<br><br>Incineration Criteria, Selection of Incineration Systems |
| M-5 | Papers to be presented at the American Institute of Chemical Engineers Conference. Cleveland, Ohio (September 1982). |

APPENDIX B

QUESTIONNAIRE USED IN INDUSTRIAL SURVEY

THERMAL PROCESS QUESTIONNAIRE

Company Name: ______________________________

A. PROCESS DESCRIPTION: A general conceptual description of the candidate process itemizing the major components is needed. A process flow diagram would be preferred.

B. STATUS OF TECHNOLOGY (Check one):

(1) Commercially available_____ Pilot Plant_____ Bench Scale_____ Lab Scale_____ Conceptual_____

(2) Probability of successful development within 5 years?____________

(3) Expected scale-up accuracy?____________

## Evaluation Criteria

To properly evaluate processes, answers to questions on the subjects described below are needed. A brief statement as to the source of the information (e.g., pilot plant data) would also be beneficial.

C. FEEDSTOCK REQUIREMENTS:

(1) What feedstocks can the process accept?

____Liquid Agents

____Combustible Solids

____Non-combustible Solids

____Contaminated Aqueous Alkaline Solutions

____Etc.

(2) What is the maximum size of feedstock? ____________

(3) Are there other restrictions on physical form? ____________

____________________________________________

(4) What is the acceptable concentration range? ____________

(5) What is the expected throughput? ____________

(6) Can the process accept explosives and propellants? Yes ____ No ____

(7) Are there any other feedstock limitations or contraints? ____________

____________________________________________

D. ENERGY REQUIREMENTS:

(1) Type of energy? Fuel____ Electrical____ Etc.____________

(2) Amount of energy per unit of feed? ____________________________

(3) Amount of energy recovered for other purposes?________________

E. EFFLUENTS, BY-PRODUCTS, AND/OR WASTES:

(1) What are the post processing clean-up requirements?__________

____________________________________________________________

____________________________________________________________

(2) What is the recommended methodology? ___________________________

____________________________________________________________

(3) What are the alternate products? ______________________________

____________________________________________________________

(4) Are there alternatives? _______________________________________

____________________________________________________________

F. THERMAL DESTRUCTION POTENTIAL:

(1) What is the projected destruction efficiencies? ______________
Agent ____________ Explosives ____________ Metal Parts ________

(2) What factors affect these? ____________________________________

____________________________________________________________

G. RELIABILITY:

(1) What are the probabilities of a system upset occurring? __________

____________________________________________________________

____________________________________________________________

(2) What are the consequences of the occurrence of a system upset? _____

____________________________________________________________

____________________________________________________________

(3) What is the anticipated availability of the process? ____________
(What fraction of total time is required for planned or unplanned maintenance? ______Planned ______Unplanned)

(4) What is the mean time between failures? ________________________

H. SAFETY:

(1) Are any extraordinary safety precautions required? ______________

______________________________________________

I. COMPLEXITY:

(1) What types of control and/or monitoring systems are required? ____

______________________________________________

(2) What are the skill level requirements of the operators? ________

______________________________________________

J. CAPITAL COSTS:

(1) What are the project costs of the required hardware? __________

______________________________________________

______________________________________________

(2) What are the space and building construction requirements? ______

______________________________________________

______________________________________________

K. OPERATING COSTS:

(1) Manpower Requirements ______________________________

(2) Maintenance ______________________________

(3) Utilities ______________________________

(4) Thermal Efficiency ______________________________

Please return questionnaire by September 27, 1982 to:

Mr. David R. Hopper
Task Leader, Industrial Survey
Battelle's Columbus Laboratories
505 King Avenue
Columbus, OH 43201

# APPENDIX C

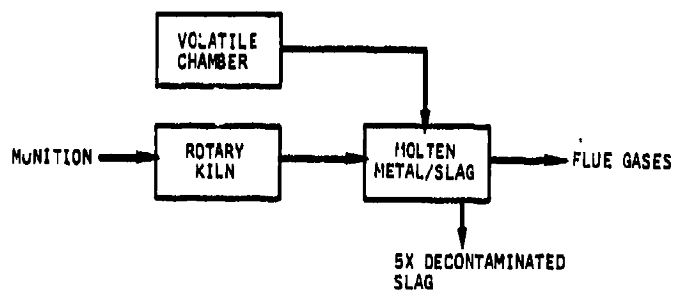
# THERMAL PROCESS DESCRIPTIONS

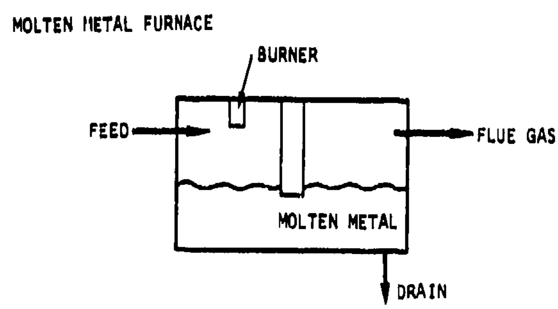
PROCESS NO. 1

ROTARY KILN (COCURRENT)/MOLTEN METAL

DESCRIPTION: Sawed munitions and associated agent are fed into a cocurrent rotary kiln. Agent contained in ton containers can first be vaporized in volatile chamber. The flue gas and metal parts exiting the kiln are fed into a baffled molten metal furnace. A reactive slag can be used in the molten metal furnace in order to reduce pollution control requirements.

FLOW DIAGRAM:




STATUS: Conceptual

ADVANTAGES: Reduced pollution control requirements. Slag and flue gases can be rendered 5X decontaminated. Large range of munitions can be processed.

DISADVANTAGES: Problems associated with typical rotary kilns, such as:

- High capital cost
- Low thermal efficiency
- Problems maintaining seals at ends of kiln

High pressures required for flue gases to overcome pressure drop associated with metal bath.

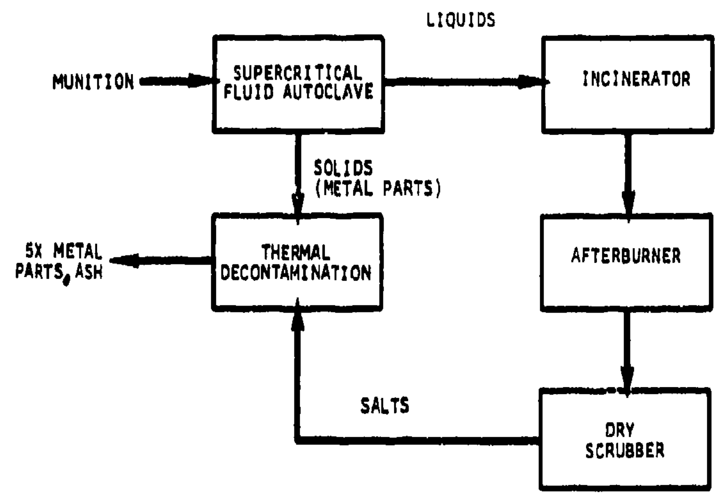
REMARKS: Worth further consideration

PROCESS NO. 2

SUPERCRITICAL FLUID (THERMAL DOWNLOAD)

DESCRIPTION: Punched munitions (agent and explosive exposed) are fed to a supercritical fluid autoclave where agent is dissolved into solution and explosive destroyed. The solution is flashed into an incinerator. Solids (metal parts) and salts from a dry scrubber are then thermally decontaminated.

FLOW DIAGRAM:




STATUS: Conceptual

ADVANTAGES: Supercritical fluid could possibly reduce agent to a less toxic form.

DISADVANTAGES: Danger of explosion when exposing munition to supercritical fluid.
High operating cost associated with maintaining high pressures in autoclave.

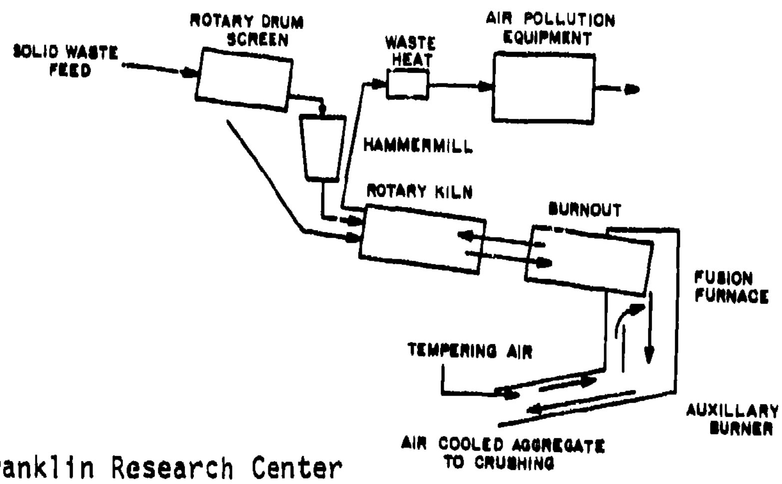
REMARKS: Extensive development required

# PROCESS NO. 3

## ECOROCK

DESCRIPTION: High-temperature (2200 F) incineration or pyrolysis of waste and subsequent incorporation of solid residue in a high quality highway-paving aggregate. Wastes are dried and combusted in a rotary kiln (1800 F). Solid residue is slagged in a firebrick furnace (2200 F) and cooled to form a solidified melt. The solid is crushed and used in production of paving aggregate.

FLOW DIAGRAM:




MANUFACTURER: Franklin Research Center

APPLICATIONS: Not yet applied to hazardous wastes

STATUS: Experimental to Pilot

ADVANTAGES: High temperatures lead to high desctuction efficiency.
Residue sealed in a non-leaching end product.
Major energy requirements can be supplied by feedstock.
End product is marketable.

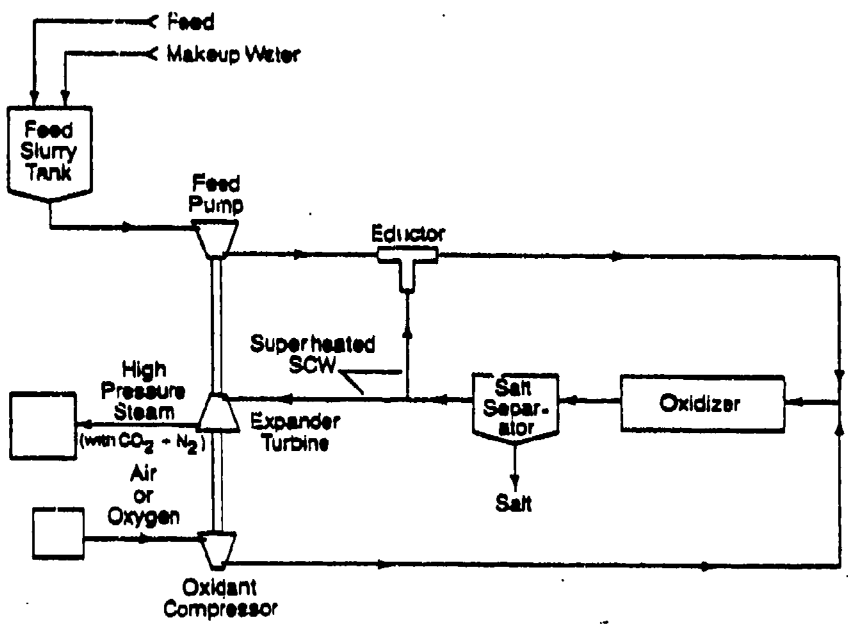
DISADVANTAGES: Potential materials compatability problems.
Ash chemistry is unknown.

PROCESS NO. 4

SUPERCRITICAL FLUID

DESCRIPTION: Oxidation of waste material using water in the supercritical state as the process medium (374 C, 3200 psi).

FLOW DIAGRAM:




MANUFACTURER: MODAR Inc., Arthur D. Little

APPLICATIONS: Various organic wastes (DDT, PCBs)

STATUS: Experimental to Pilot Scale

COST: Modar
- 2500-25,000 gal/day-
- Operating - \$.10 to \$2.00/gal
- Capital - unknown

ADVANTAGES: Advantages over wet-air oxidation include:
- Less expensive capital cost due to the use of a tubular reactor instead of an autoclave
- No need for additional processing of waste.

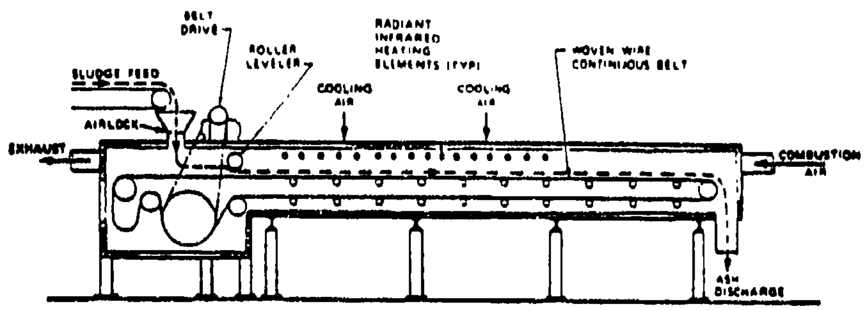
DISADVANTAGES: High pressures and associated compression costs.

# PROCESS NO. 5

## ELECTRIC FURNACE (INFRARED)

DESCRIPTION: A horizontal, rectangular, ceramic fiber blanket-lined, steel shell containing a moving horizontal woven-wire belt and radiant heating elements.

FLOW DIAGRAM:




MANUFACTURER: Shirco Inc., Midland-Ross

APPLICATIONS: Toxic sludges, solids

STATUS: Commercially available

COST: 50 M gal/day 20 percent solids:
Capital - $1.5M (without cleanup e.g.)
Operating - cost of 50 hp

ADVANTAGES: Low capital cost
Low operation and maintenance costs (waste heated by radiation)
No explosion danger
Easy shutdown and start up (possible intermittent operation)

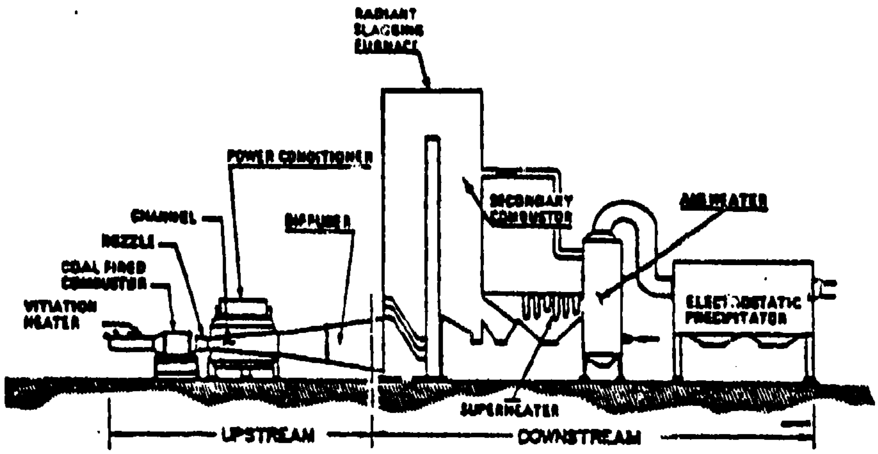
DISADVANTAGES: Large floor space requirement; gas clean up required; resistant heaters susceptible to frequent burnout; can only be used on slurries that contain at least 15 percent solids.

# PROCESS NO. 6

## MAGNETOHYDRODYNAMICS

DESCRIPTION: Combustion of coal at slagging temperatures (5000 F) and subsequent acceleration of flue gas through a nozzle into a magnetohydrodynamic generator.

FLOW DIAGRAM:




MANUFACTURERS: University of Tennessee, TRW

APPLICATION: No known hazardous waste treatment

STATUS: Experimental

ADVANTAGES: High potential for energy recovery

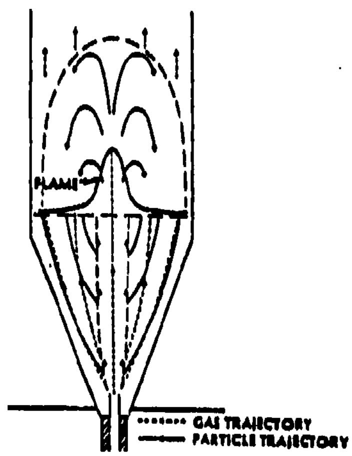
DISADVANTAGES: Highly likely to encounter materials compatability problems.

PROCESS NO. 7

SPOUTED BED

DESCRIPTION: Injection of gas at high velocity through a small central operature into a cylindrical vessel filled with coarse solid particles. A cyclical pattern of movement is formed as particles peak in center of cylinder and return to bottom along cylinder wall.

FLOW DIAGRAM:




MANUFACTURER: Battelle Memorial Institute

APPLICATION: No known application to hazardous wastes

STATUS: Experimental

ADVANTAGES: Low heating value fuels can be incinerated due to good heat recirculation; advantages over conventional fluidized beds: lower pressure drops, better mixing; higher residence time capability.

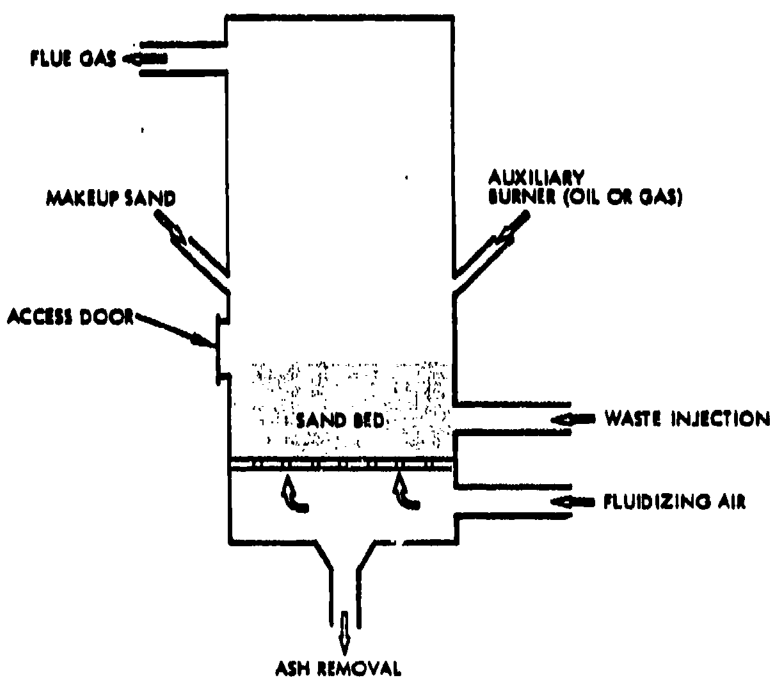
DISADVANTAGES: High potential for gas short circuiting bed, primarily used to react on solids.

PROCESS NO. 8

## FLUIDIZED BED

DESCRIPTION: A vertically oriented vessel in which gases are blown up through a bed of inert granular material. The agitation of the bed creates a dense, well-mixed medium which behaves like a liquid. Wastes are injected into or just above the bed. An auxilliary fuel is used to preheat or maintain bed temperature.

FLOW DIAGRAM:




MANUFACTURERS: Lurgi, General Atomic Copeland Systems, Energy Inc., Scientific Design, Aerojet

APPLICATIONS: Primarily used for the destruction of sludges from municipal wastewater plants, oil refineries, and pulp and paper mills. Some work with organics such as PCBs, pharmaceutical wastes, phenolic wastes, and methyl methacrylate has been performed.

STATUS: Commercially available

PROCESS NO. 8

FLUIDIZED BED (continued)

COSTS: Costs estimated by Energy Incorporated for 50 gal/hr unit:

Installed cost - $1.3 million
operating cost $.25/pound of waste

ADVANTAGES: Applicable for solid, liquid, and gaseous combustible wastes.

Simple design requiring no moving parts.

Compact due to high heating rates, reduces capital cost.

Low temperatures and excess air requirements, lower $NO_x$ emissions which could reduce emission control costs.

Gaseous emissions can be controlled by paper bed material selection

High combustion efficiencies.

DISADVANTAGES: Difficult to remove residual materials from the bed.

Temperatures can not exceed softening point of the bed to avoid agglomeration.

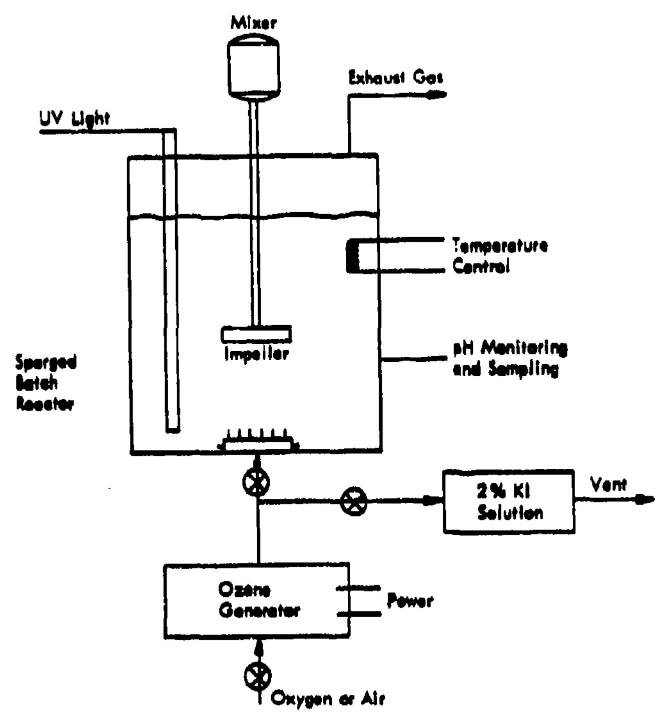
High operating cost.

PROCESS NO. 9

UV DECOMPOSITION (PHOTOLYSIS)

DESCRIPTION: Degradation of wastes using ultraviolet light. Ultra-light may be supplied by sunlight, lamps, or lasers. In addition, some processes involve the bubbling of ozone through waste for oxidation.

FLOW DIAGRAM:




MANUFACTURERS: Houston Research
Westgate Research (ozonation)
Southern Illinois University
University of California (laser)
FOCUS (solar)
Atlantic Research Corporation
QED (solar zapper)

APPLICATION: PCBs

ADVANTAGES: Potential for removing pollutants prior to final destruction.

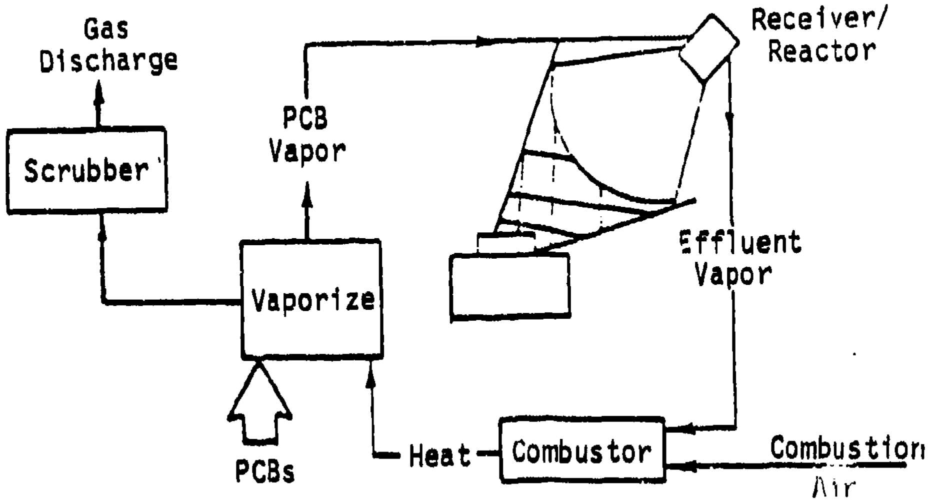
DISADVANTAGES: Designed for liquids and many other toxic compounds

PROCESS NO. 10

# SOLAR ZAPPER

DESCRIPTION: SOLAR ENERGY, CONCENTRATED TO 10,000 TIMES AMBIENT LEVELS, IS USED TO THERMALLY AND PHOTOCHEMICALLY DEGRADE HYDROCARBONS. THE PYROLYSIS PRODUCTS ARE SUBSEQUENTLY INCINERATED

FLOW DIAGRAM:




MANUFACTURERS: FOCUS ENVIRONMENTAL SYSTEMS

PREVIOUS APPLICATIONS: DESTRUCTION OF PCBs

STATUS: PILOT PLANT

ADVANTAGES: LOW OPERATING COSTS
UTILIZES SYNERGISM OF THERMAL AND PHOTOCHEMICAL

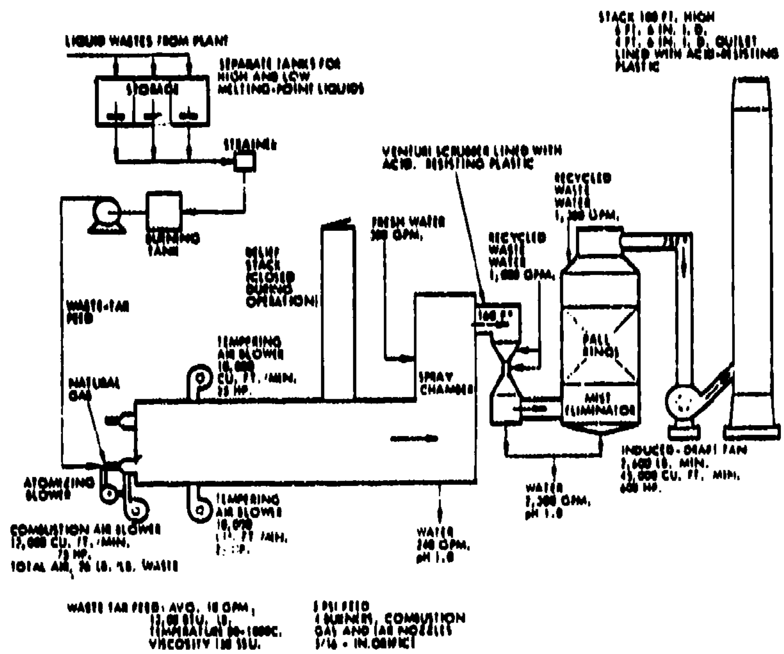
DISADVANTAGES: TECHNOLOGY IS NOT WELL UNDERSTOOD

EVALUATION: A UNIQUE COMBINATION OF MECHANISMS THAT HAS POTENTIAL FOR AGENT DESTRUCTION

PROCESS NO. 11

LIQUID INJECTION

Description: Incinerator which destroys liquids and slurries by atomizing the waste by atomizing the waste and mixing it with air. Atomization achieved either mechanically, using a rotary cap or pressure atomization systems, or via gas-fluid nozzles which use high pressure air or steam. Incinerator can be oriented horizontally or vertically with injection along the central axis. In a specialized liquid injection combustor, the vortex, waste injected tangentially.



MANUFACTURERS: Air Resources, Bigelow-Liptak, Brule, C&H Combustion, Hirt Engineers, Inc., Midland-Ross, John Zinc, Met-Pro, Peabody International, Prenod, Trane Thermal

STATUS: Commercially available.

APPLICATIONS: PCBs, pesticides, herbicides, polymer wastes, phenols, still and reactor bottoms

PROCESS NO. 11

LIQUID INJECTION (continued)

COST: 4500 metric tons/yr hexachlorocyclopentadiene
Capital - \$1.63M
Operating \$4.92/metric ton

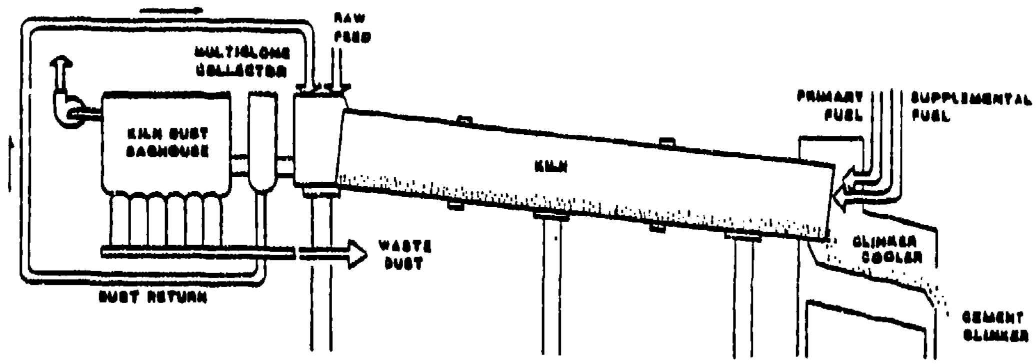
ADVANTAGES: Capable of incinerating a wide range of liquid wastes
Low maintenance cost due to lack of moving parts
Capable of fairly high turndown ratio

DISADVANTAGES: Only wastes that can be atomized through a burner nozzle can be incinerated.
Burners susceptible to pluggage.

PROCESS NO. 12

## CEMENT KILN

DESCRIPTION: Integration of waste incineration with a process used in cement manufacture. Waste, limestone, and cement additives are fed to a rotary kiln and subjected to 2600 F temperatures and residence times of up to 10 seconds. End product is the solid clinker found in cement.




MANUFACTURERS: Alpha Portland Cement Co., General Portland Co., SCA Services, Inc. (Chem-Thol), St. Lawrence Cement Co., Marquette Cement Company.

STATUS: Commercially available technology.

COSTS: Possible savings in cement production costs if waste has significant heating value.

APPLICATIONS: Hard to burn wastes have been successfully destroyed in test burns. Less hazardous materials such as waste solvents and still bottoms from solvent reclaiming operations have already been purchased and burned on a continuous basis by cement companies.

ADVANTAGES: High temperatures and long residence times are well-suited for hazardous waste destruction.
Wastes may decrease production costs if they have fuel value.
Chlorinated wastes neturalize alkaline clinkers.

PROCESS NO. 12

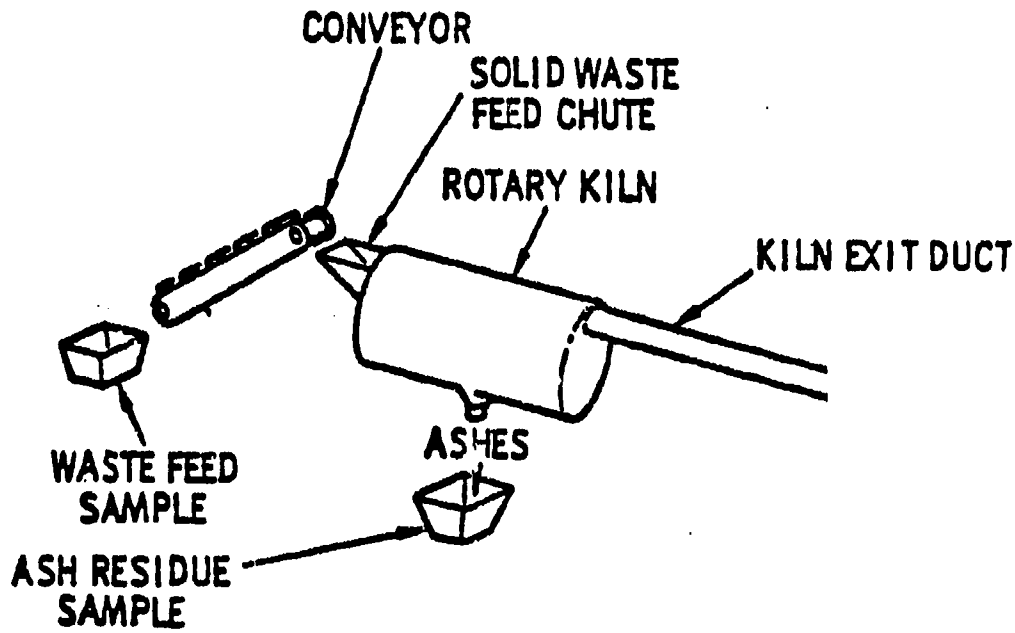
CEMENT KILN (continued)

DISADVANTAGES: Increase in particulate matter in the waste stream.
Lack of public support.

PROCESS NO. 13

ROTARY KILN

DESCRIPTION: A cylindrical refractory-lined shell that is mounted at a slight incline from the horizontal. Rotation of the shell mixes waste with combustion air and transports the waste through the kiln. Handles liquids, solids, and gases.




MANUFACTURERS: Midland Ross, Lurgi, Bigelow-Liptak, C&H Combustion, Met-Pro, Vulcan Iron Works, TRW Systems, Inc., C.E. Raymond, Franklin Research Center, Brown Engineering, Versar, Thermall, Ford, Bacon & Davis, Stock Equipment, Kyle Machine Works.

APPLICATIONS: PCB wastes, munitions, chemical warfare agents, polyvinylchloride waste

STATUS: Commercially available.

COSTS: PCB wastes

5,000 metric tons/yr

Capital $3,648,900

Operating $741.00/metric ton (1978) dollars

PROCESS NO. 13

ROTARY KILN (continued)

ADVANTAGES:

Able to incinerate wastes in any physical form.
Capable of accepting wastes from a variety of feed mechanisms.
Feed capability for drums and bulk containers.
No moving parts inside kiln.
Can operate at high temperatures (> 2500 F).

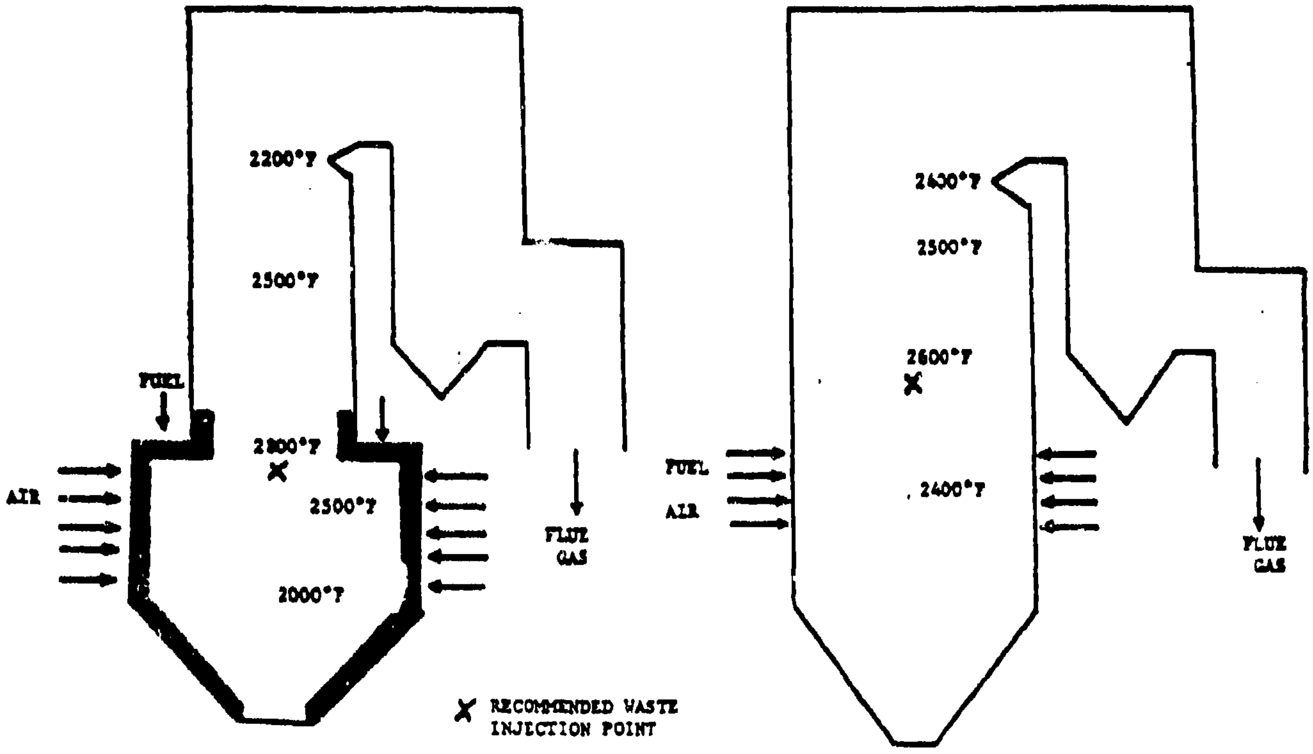
DISADVANTAGES:

High installation cost.
Particulate matter entrained and carried out of reactor before complete combustion.
Low thermal efficiency.
Problems arise maintaining seals at ends of the kiln.

PROCESS NO. 14

INDUSTRIAL BOILERS

DESCRIPTION: Cocumbustion or use of waste as fuel in devices, whose primary purpose is energy production, such as industrial boilers and process heaters.




(a) ANTHRACITE BOILER (b) BITUMINOUS BOILER

APPLICATIONS: PCB contaminated material, waste oil, wood-pulping waste, petroleum refining fuels.

STATUS: Commercially available.

ADVANTAGES: Use of existing facilities.

DISADVANTAGES: Previously used for high heat content wastes which are content wastes which are usually not considered hazardous. May shorten useful life of boiler

PROCESS NO. 15

## INTERNAL COMBUSTION ENGINE

DESCRIPTION: A Dorman 6-cylinder, 113 kw, tubocharged, 4-stroke diesel engine.

MANUFACTURER: D & D Group

APPLICATIONS: PCB/TCB

DESTRUCTION EFFICIENCY: 99.95 percent

STATUS: Pilot to commercial

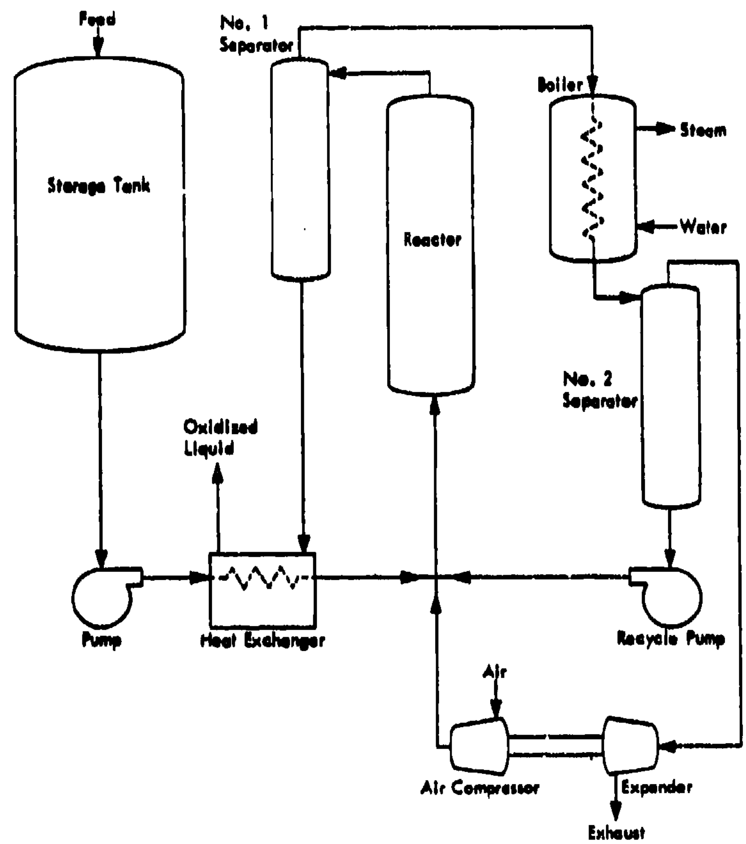
ADVANTAGES: Possible to obtain both high temperature and high pressure, high potential for meaningful energy recovery.

DISADVANTAGES: Limited feedstock.

# PROCESS NO. 16

## WET-AIR OXIDATION

DESCRIPTION: Aqueous phase oxidation of dissolved or suspended organic substances at elevated temperatures and pressures (350-650 F and 300-3000 psig). Catalysts are sometimes employed.




MANUFACTURERS: Zimpro Inc., Energy and Environmental Systems

APPLICATIONS: Municipal sludge, acrylonitrile, pulping liquor, explosives, pesticides, pharmaceutical wastes.

STATUS: Commercially available.

COSTS: Installed capital costs

1.6 M/10 gpm - 5.5 M/70 gpm

Operating

1.7 cents/gallon - 3.7 cents/gallon

Maintenance

1 - 2 percent of plant fixed capital investments (1982)

PROCESS NO. 16

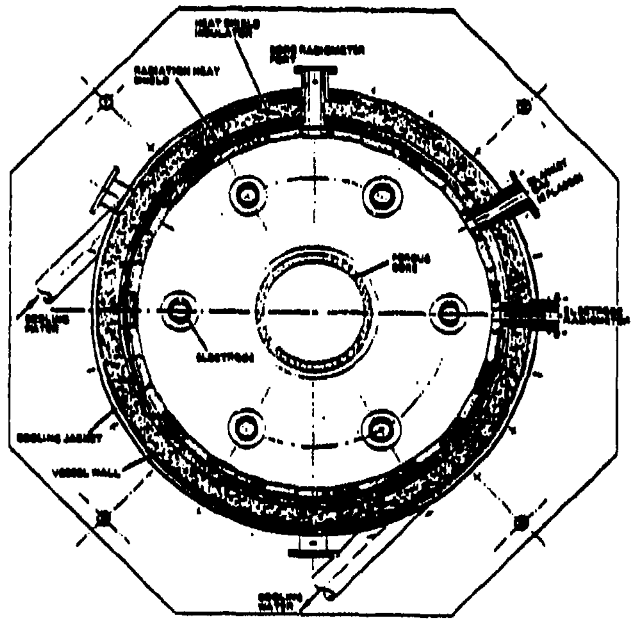
WET-AIR OXIDATION (continued)

| | |
|---|---|
| ADVANTAGES: | Low operating cost |
| | Low heating value feedstocks can be used |
| DISADVANTAGES: | Limited to dilate solutions |
| | Extensive downstream processing may be required. |

PROCESS NO. 17

## HIGH-TEMPERATURE FLUID WALL

DESCRIPTION: Finely ground (-20 mesh) or atomized wastes are destroyed via radiant energy. Wastes are fed downward into a porous, tubular core. The core is heated by electrodes which are located outside of the pourous core and an outer wall. A gas (transported to radiation) is injected into the pourous core radially to blanket walls and reduce contact between them and waste material.




MANUFACTURER: Thagard Research Company

APPLICATION: Hexachlorobenzene

STATUS: Pilot scale/commercial.

COSTS: Thagard claims are comparable to conventional incineration.

ADVANTAGES: Reduced need for downstream stack clean up devices.
Longer life due to fluid wall.

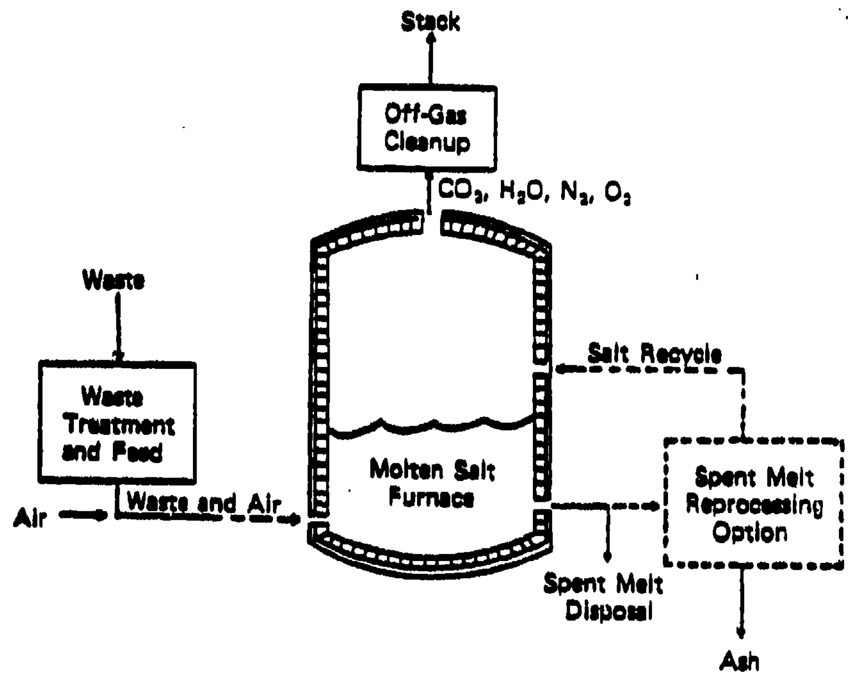
DISADVANTAGES: Feed must be ground or atomized.

PROCESS NO. 18

SINGLE STAGE MOLTEN SALT

DESCRIPTION: TOXIC CHEMICALS AND CONTAMINATED MATERIAL ARE COMBUSTED AND DISSOLVED IN A MOLTEN SALT BATH AT 800 TO 1000°C. ACID GAS COMPONENTS ARE RETAINED IN THE SALT.

FLOW DIAGRAM:




MANUFACTURERS: ROCKWELL INTERNATIONAL, QUESTEX CORPORATION

PREVIOUS APPLICATIONS: DISPOSAL OF EXPLOSIVES, WAR GASES, PESTICIDES, PCB'S AND OTHER INDUSTRIAL WASTES

STATUS: PILOT TO COMMERCIAL

DESTRUCTION EFFICIENCIES: SIX NINES OR BETTER IN ROCKWELL BENCH SCALE TESTS WITH WAR GASES

COSTS: ROCKWELL ESTIMATED THE COST OF A COMPLETE PLANT TO PROCESS 1000 LB/HR OF NEUTRALIZED GB TO SODIUM PHOSPHATE FOR RESALE IN 1975 AS $2MM

PROCESS NO. 18

ADVANTAGES: HIGH DESTRUCTION EFFICIENCY, MINIMAL OFF-GAS CLEAN-UP REQUIREMENTS, LOW WASTE VOLUME, SPENT SALT HAS BEEN 5X DECONTAMINATED

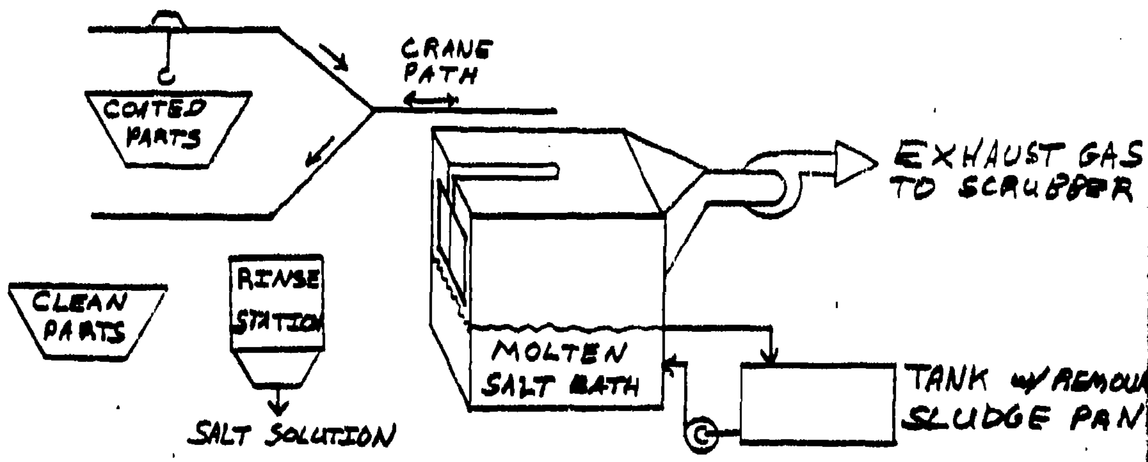
DISADVANTAGES: COSTS MAY BE HIGH, BULK METAL FEED IS DEVELOPMENTAL AT BEST, $P_2O_5$ EMISSION IS LIKELY

PROCESS NO. 19

MOLTEN SALT METAL CLEANING

DESCRIPTION: PARTS ARE LOWERED FROM AN OVERHEAD CRANE INTO A MOLTEN SALT BATH AT 200 TO 550ºC, ENCLOSED IN A FUME HOOD. PARTS ARE THOROUGHLY CLEANED BY OXIDIZING SALT WITH MINIMUM ATTACK OF THE METAL

FLOW DIAGRAM:




MANUFACTURER: KOLENE CORPORATION

PREVIOUS APPLICATIONS: DESCALING, REMOVAL OF RAINT, TEFLON AND MOLYBDENUM DISULFIDE COATINGS

STATUS: WIDELY USED IN INDUSTRY

ADVANTEGES: MAY PROVIDE MORE THOROUGH OR RAPID DECONTAMINATION AND REQUIRE LESS ENERGY THAN CONVENTIONAL FURNACE TREATMENT

DISADVANTAGES: HAS NOT BEEN TESTED WITH HAZARDOUS MATERIALS

PROCESS NO. 20

# THERMAL PLASMA SYSTEMS

| | |
|---|---|
| DESCRIPTION: | PLASMA TORCH CONVERTS ELECTRICAL ENERGY TO PROCESS HEAT VIA A RAPIDLY ROTATING ELECTRIC ARC. THIS SYSTEM CAN BE USED TO OXIDIZE OR PYROLYZE AT EXTREMELY HIGH TEMPERATURES (+2000°F). THE HYDROCARBONS ARE CONTAINED IN A GAS STREAM |
| MANUFACTURERS: | WESTINGHOUSE APPLIED ENERGETICS, PLASMA RESEARCH, INC. |
| PREVIOUS APPLICATIONS: | HYDROCARBON PYROLYSIS, BLAST FURNACES |
| STATUS: | PILOT PLANT |
| ADVANTAGES: | HIGH DESTRUCTION EFFICIENCY<br>LOW PRODUCT GAS VOLUME<br>LOW CAPITAL COSTS |
| DISADVANTAGES: | HIGH OPERATING COSTS<br>CAN'T PROCESS METAL PARTS<br>PREDICTION OF PRODUCTS IS DIFFICULT |
| EVALUATION: | HIGH POTENTIAL FOR AGENT DESTRUCTION. MAY BE INCORPORATED AS AN ENERGY SOURCE IN AN OVERALL CONCEPT |

PROCESS NO. 21

# MOLTEN METAL

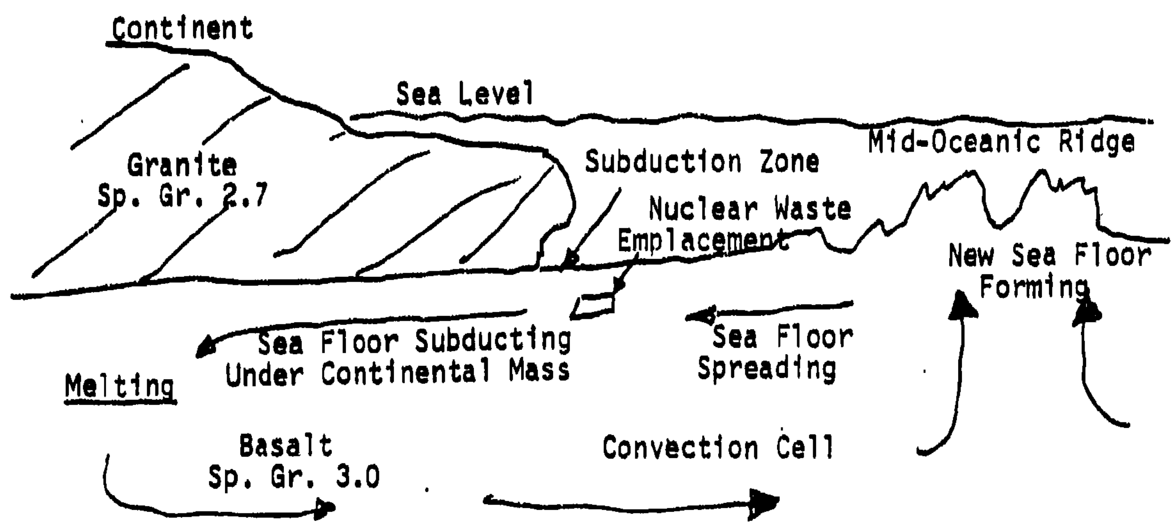
| | |
|---|---|
| DESCRIPTION: | CONTAMINATED MATERIAL IS FED TO A BED OF MOLTEN METAL (IRON, SODIUM, ETC.). AGENT IS EITHER OXIDIZED OR PYROLYZED AND ASH FORMS A SLAG |
| MANUFACTURERS: | PYROMAGNETIC, MINE SAFETY APPLIANCE |
| PREVIOUS APPLICATIONS: | COAL GASIFICATION, MUNICIPAL WASTE DISPOSAL |
| STATUS: | PILOT TO COMMERCIAL |
| ADVANTAGES: | POTENTIAL FOR HIGH TEMPERATURE OPERATION<br>SOLID RESIDUE IS 5X DECONTAMINATED<br>POTENTIAL FOR CATALYSIS OR REACTIVE MEDIUM IN BED<br>ACCEPTS A VARIETY OF FEEDSTOCKS |
| DISADVANTAGES: | SHORT VESSEL LIFE<br>HIGH OPERATING COSTS<br>SLAG CHEMISTRY IS UNKNOWN<br>MAY REQUIRE TOP FEED |
| EVALUATION: | HIGH POTENTIAL BUT LAB TESTING IS REQUIRED |

PROCESS NO. 22

# GEOTHERMAL

CONCEPT: DEPOSIT HAZARDOUS WASTES ON THE OCEAN FLOOR IN A SUBDUCTION ZONE WHERE THEY WILL BE CYCLED TO THE EARTH'S CORE AND MELTED BY GEOTHERMAL PROCESS

DIAGRAM:




PRESENTLY BEING CONSIDERED FOR NUCLEAR WASTE DISPOSAL

EVALUATION: ACCEPTANCE UNLIKELY FOR POLITICAL REASONS

# PROCESS NO. 23

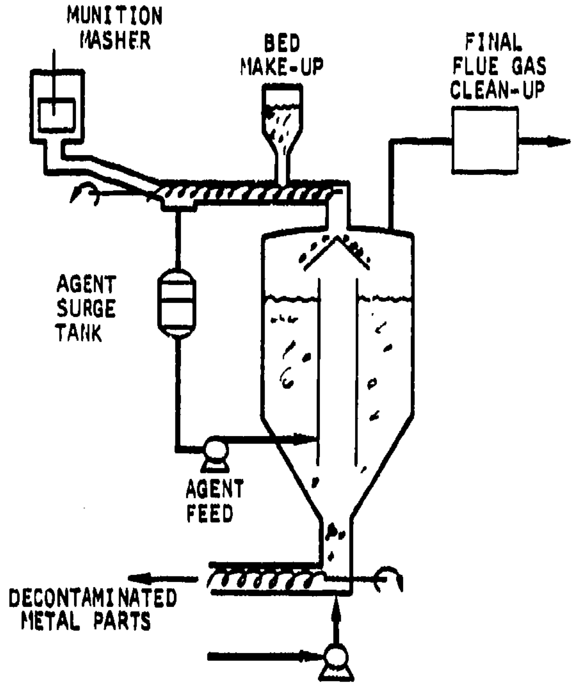
## MASHED MUNITION FLUIDIZED-BED

DESCRIPTION: A fluidized-bed incinerator designed to process a "munition mass" consisting of projectile pieces (metal parts 1-6 inches), propellant/explosive pieces (1-6 inches), and chemical agent. The incinerator consists of a cylindrical vessel with a conical bottom connected to a bulk item conveying system. Inside the vessel, a spout tube would be suspended along the vertical axis of the vessel and would be placed about one foot above the cone exit and would extend to about one foot above the bed material near the top of the vessel.

The munition mash exiting a "munition masher" would enter the metal parts and explosive/propellant feed system. At this point, liquid agent would be collected and would drain into an agent surge tank. Make-up bed material would be added to the metal parts feed and the mixture would be fed into the incinerator and randomly distributed into the annular bed area by the conical distributor plate. Since the bed material is not static but is moving downward in the annulus, the metal parts and explosive/propellants work their way downward and are respectively decontaminated and deactivated by the bed material which is about 1600 F. As the pieces enter the conical discharge section, the large metal parts fall into the bulk item discharge conveyor where any adhering bed material is swept away by the jet of air which enters at the bottom. Explosive/propellant materials that are not entirely deactivated would be completely combusted by the jet of air. Therefore, only deconned metal parts exit at the bottom of the incinerator. The jet of air in addition to sweeping the metal parts would sweep bed material up into the spout tube where the chemical agent is injected. Complete combustion of the agent would occur within the spout tube and the acid product gases produced by the combustion process would react with the limestone providing for an in-situ scrubbing capability. The combustion product gases and bed material would pass up the spout tube where in the freeboard area the bed material would fall into the annular area (giving the annulus its moving bed feature) and the product gases would exit the incinerator for final flue gas treatment. The freeboard area also provides for additional residence time to insure complete destruction of the agents. The heat generated by the combustion process within the spout tube would be distributed throughout the bed by circulation of the bed material as well as by conduction through the spout tube.

MASHED MUNITION FLUIDIZED-BED (continued)

DIAGRAM:




STATUS: Conceptual

ADVANTAGES: Possibility of destroying agent, deactivating explosive/propellants, deconning metal parts all in one unit

Some scrubbing of acid gases could be achieved when limestone added to bed material

DISADVANTAGES: Possible difficulty in achieving the proposed feed and metal parts removal scenarios

Proposed temperature of bed material is above softening point of common lime (approximately 1300 F) which may lead to agglomeration

Agglomeration may be enhanced by interaction between bed material and agent in the spout

PROCESS NO. 24

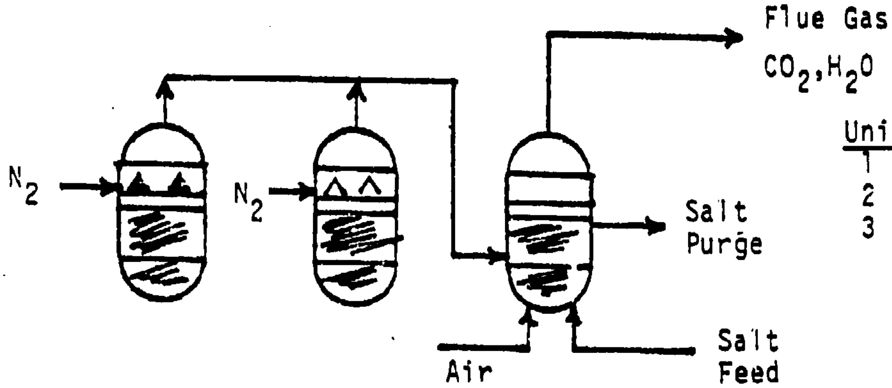
SWINGING MOLTEN SALT

DESCRIPTION: A modification of molten salt incineration in which the volatilization, burnout, and incineration of munitions/items is rotated between at least three molten salt units. Each unit alternately provides one of these three functions. The process would require minimum amounts of auxiliary fuel and effectively utilizes the agent heat of combustion for volatilization and burnout. Furthermore, the incineration unit provides for the in-situ scrubbing of the acid product gases and could also destroy spent decon solution which would help in controlling the incineration temperature.

Referring to Cycle I in the diagram, Unit 1 is in the volatilization mode. A tray of projectiles, TCs, or bombs is placed in the vessel and occupies the freeboard area above the molten salt bath. The temperature of the bath is about 1800 F and radiation from the bath to the munitions is the dominant mode of heat transfer. The agent is rapidly volatilized in an inert atmosphere and conveyed to the incinerator, Unit 3. Calculations indicate that a 6-foot diameter by 6-foot depth bath can volatilize the agent in 150 105 projectiles (placement density of 50 percent) with a decrease of only about 100 F in bath temperature. This would equal a destruction rate of approximately 1000 lbs/hr. Prior processing of the munitions would only require that the explosive/propellant be removed and that the agent cavity be accessed. Unit 2 is in the burnout phase wherein the final residual amounts of agent are removed and the metal parts decontaminated. The residual quantities of agent would also be conveyed to Unit 3 for incineration. Unit 3 is in the incineration mode receiving agent vapors as well as combustion air. At the end of this cycle, Unit 3 would be the hottest unit since it was the incinerator, followed by Unit 1 and Unit 2. In Cycle II, a new charge of munitions is placed in Unit 3, which now serves as the volatilizer; the metal parts in Unit 1 remain for burnout; and Unit 2 is thermally recharged and serves as the incinerator. Thus, the various functions of volatilization, burnout, and incineration are rotated among the three units to utilize efficiently the energy of combustion. The unsteady flow of agent to the incinerator would not pose a problem because of the large heat capacity of the beds; hence, control would not be a problem.

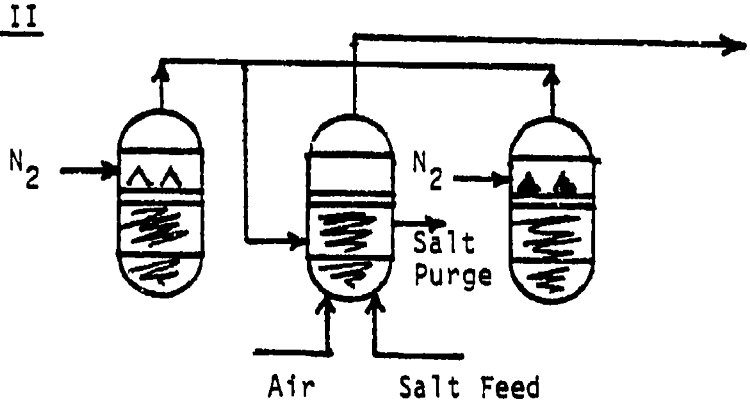
DIAGRAM: (following page)

# PROCESS NO. 24
## SWINGING MOLTEN SALT



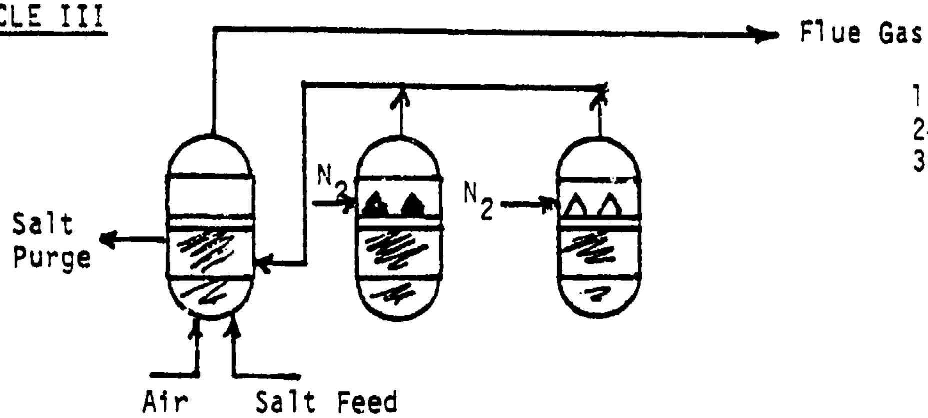

| Unit | System Status |
|---|---|
| 1 | Volatilization |
| 2 | Burnout |
| 3 | Incineration |

CYCLE II




| | |
|---|---|
| 1 | Burnout |
| 2 | Incineration |
| 3 | Volatilization |

CYCLE III




| | |
|---|---|
| 1 | Incineration |
| 2 | Volatilization |
| 3 | Burnout |

PROCESS NO. 24

SWINGING MOLTEN SALT (continued)

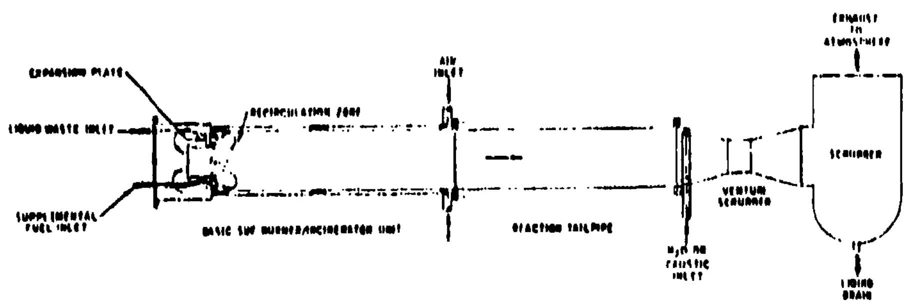
| | |
|---|---|
| STATUS: | Conceptual |
| ADVANTAGES: | Heat of combustion of agent used for volatilization and burnout |
| | Less auxiliary fuel required |
| | In-situ scrubbing of acid gases |
| | Incineration temperature could be controlled by destroying spent decon solution |
| DISADVANTAGES: | Possible problems with valving network at high temperatures |

PROCESS NO. 25

SUE BURNER

DESCRIPTION: A fume and liquid incinerator similar to liquid injection incinerators. The burner is comprised of an inlet pipe connected to a large diameter combustion chamber by means of a flat plate. Fuel nozzles protruding from the plate inject wastes radially into the inlet air stream. Combustion occurs in a recirculation zone formed by the flat plate and combustion chamber wall.

DIAGRAM:



BASIC SUE BURNER/INCINERATOR

STATUS: Commercial

PREVIOUS APPLICATIONS: Chlorinated hydrocarbons

MANUFACTURER: Marguardt Company

ADVANTAGES: Extremely stable burner
Turn down ratio of 10:1

DISADVANTAGES: Incapable of processing solids larger than 500 microns

REMARKS: Worth consideration as an afterburner

# PROCESS NO. 26

## SWINGING MOLTEN METAL

DESCRIPTION: The concept utilizes 3 molten metal baths to alternately volatilize, melt, and incinerate muntions/items containing lethal agents.

The sequence of events is as follows:

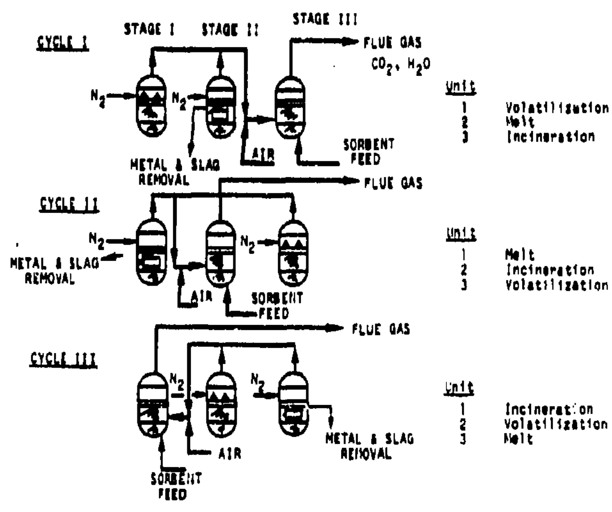
Stage 1. A muntion/item, with the agent and explosive cavities, punched and plugged, with a meltable plug is suspended above a molten metal bath. The radiant and convective heat vaporizes the agent and ignites the explosive. Volatiles are carried out with a nitrogen or air purge.

Stage 2. In Stage 2, the munition without its volatile components is dropped in to the molten metal bath for melting and hence 5X decon. Excess metal and slag are removed in this stage. Volatiles are removed via a purge flow.

Stage 3. Volatiles from the other two baths which are operating in Stages 1 and 2 enter the molten metal via a lance. Air also enters the lance causing the combustibles to burn as they bubble through the bed. An appropriate sorbent can also be fed to the bath to produce a molten slag which removes Cl, F, P, and S from the flue gas.

In the subsequent phases, the bath formerly used for incineration is used for volatilization since its temperature is the highest. The bath used to melt in the previous phase becomes the incineration chamber and the former volatilization becomes the melt bath.

FLOW DIAGRAM:



PROCESS NO. 26

SWINGING MOLTEN METAL 

STATUS: Theoretical

ADVANTAGES: Efficient use of heat of cumbustion of agent by bath rotation.

Reduced pollution control requirements if pollutants can be captured in slag.

DISADVANTAGES: High capital cost associated with the number of baths and duplication of related equipment.

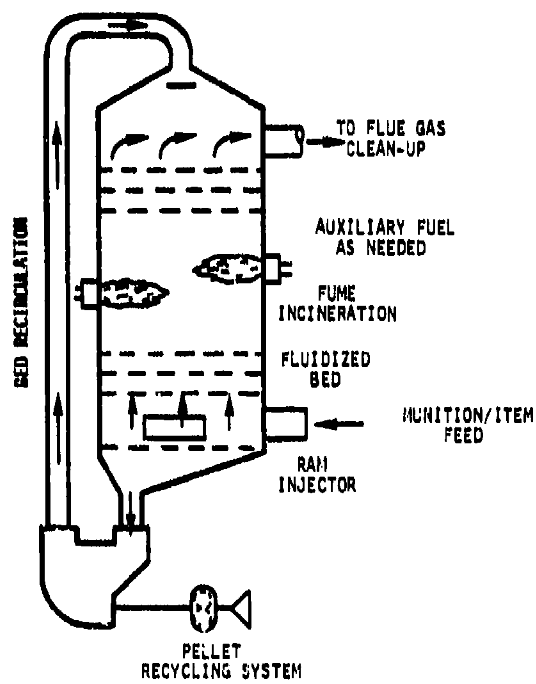
REMARKS: Worth further consideration

PROCESS NO. 27

## FLUIDIZED BED/FUME INCINERATOR
(INACTIVE)

DESCRIPTION: An adaptation of the Midland-Ross Fume Incinerator/Fluid Bed Heat Exchanger. Punched munitions are fed to the bottom of the unit by a ram injector. Falling bed material thermally downloads munitions and metal parts can be rendered 5X decontaminated. Vapors rise and are combusted as they pass through combustion zone. Burning agent and auxiliary fuel heats bed material which is recirculated.

DIAGRAM:




STATUS: Adaptation of a commercially available process

ADVANTAGES: Capable of handling larger items than conventional systems

Metal parts can be 5X decontaminated utilizing the heat generated by agent combustion

DISADVANTAGES: Possible difficulty with insuring 5X decontamination due to interaction of contaminated bed material with metal parts

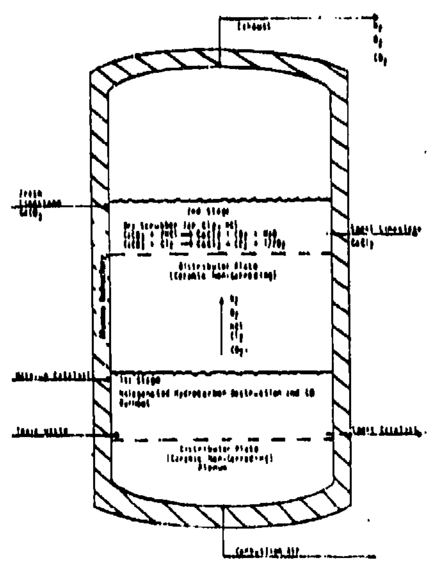
COMMENTS: Worth further consideration

PROCESS NO. 28

SEQUENTIAL FLUID BED
($E^3I$)

DESCRIPTION: A two-stage fluid bed proposed for the destruction of toxins. Toxic waste materials and make-up catalyst are fed to the first stage (a hot air fluidized bed). The toxic wastes are pyrolyzed and oxidized in the bed producing $CO_2$, HCl, and $Cl_2$. The chromia supported on alumina catalyst promotes the destruction of thermally stable toxic compounds and the oxidation of CO to $CO_2$. The exhaust gas from the first stage is used to fluidize the second stage. Limestone is added to the second stage to remove chlorine and chlorides from the exhaust stream.

DIAGRAM:



CONFIDENTIAL
PROPRIETARY INFORMATION OF ENERGY AND ENVIRONMENTAL ENGINEERING INC.

STATUS: Conceptual

PROPRIETOR: Energy and Environmental Engineering, Inc.

ADVANTAGES: The catalyst in first stage promotes the oxidation of stable toxic species and reduces the operating temperature required to induce oxidation.

PROCESS NO. 28

SEQUENTIAL FLUID BED 

ADVANTAGES:
(Con't) The second stage dry scrubbing system has the potential of removing corrosive gases from the exhaust.

Solid and liquids can be fed to the system.

DISADVANTAGES: Possible formation of eutectics leading to bed agglomeration.

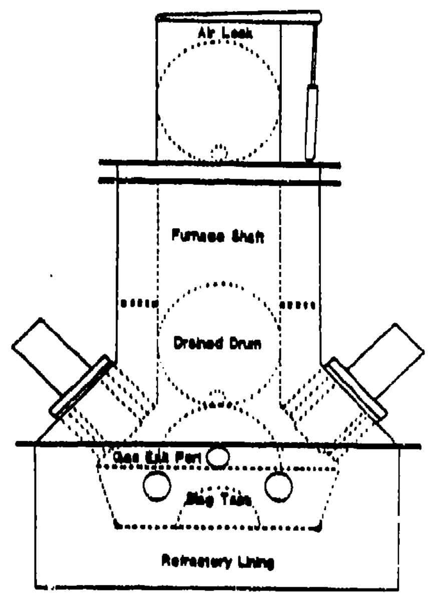
COMMENTS: Worth further consideration

# PROCESS NO. 29

## PLASMA ARC PYROLYSIS

DESCRIPTION: Containers of agent are placed in an air lock and are punched or rammed in order to release agent. The liquid agent is transferred to a reservoir and the container is dropped into a pyrolytic plasma chamber where it is melted. The liquid agent is pumped into the chamber at a fixed rate and pyrolyzed. Slag has potential for pollutant capture.

DIAGRAM:




STATUS: Conceptual

ADVANTAGES: Possible reduced pollution control equipment requirements due to capture in a reactive slag.

Slag can be rendered 5X decontaminated.

DISADVANTAGES: Limited feedstock configurations
High operating cost

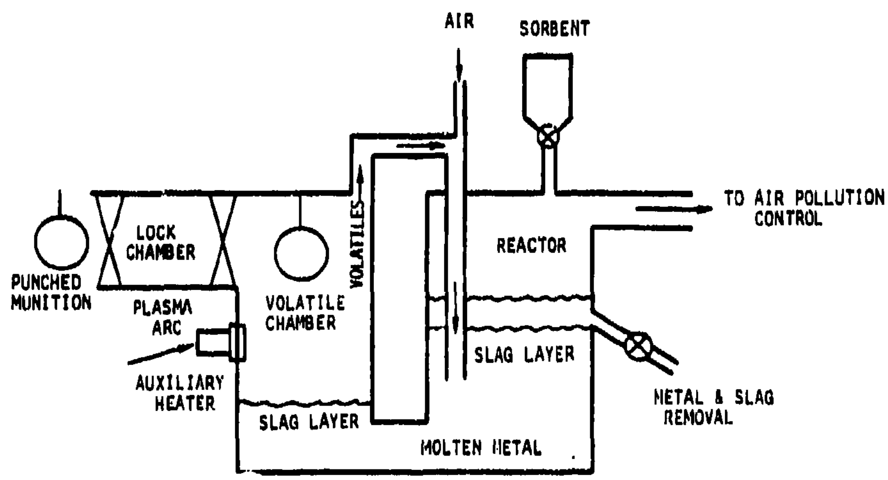
REMARKS: Worth further consideration

PROCESS NO. 30

MOLTEN METAL/SLAG THERMAL DOWNLOAD

DESCRIPTION: Punched munitions are fed to a volatile chamber where heat from the molten metal bath and auxiliary heater (plasma arc) volatilize the agent and explosive. The munition body can be melted and/or dropped into the molten metal for 5X decontamination. The volatiles are mixed with air and injected, through a lance, under the surface of the molten metal in the reaction chamber. Sorbent is added and forms a slag layer on the surface of the molten metal. The slag layer captures halogens phosphorous, and/or sulfur. The volatile chamber and reaction chamber are interconnected to permit the flow of metal and slag from the volatile chamber to the reaction chamber for removal. The molten metal may also reduce heating requirements in the volatile chamber by conductively transferring the heat generated in the reaction chamber.

DIAGRAM:




STATUS: Conceptual

ADVANTAGES: Reduce pollution control requirements

5X decontamination of metal parts in metal bath

Heat generated in reaction chamber compliments auxiliary burner in volatilizing items

DISADVANTAGES: High gas pressures may be required to overcome pressure drop associated with the molten metal bath.

Materials problems at temperatures high enough to melt munitions.

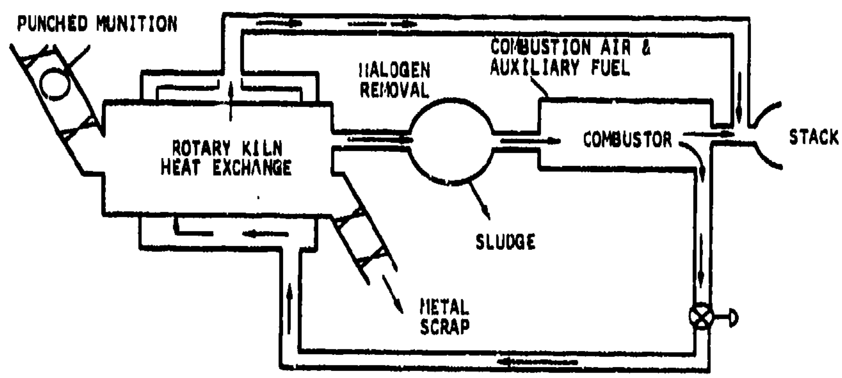
REMARKS: Worth further consideration

# PROCESS NO. 31

## ROTARY KILN
## (Pyrocal Process)

DESCRIPTION: Punched munitions enter the rotary kiln heat exchanger where the explosives and agent are volatilized and pyrolyzed. The pyrolysis gases enter a clean-up device where the halogens and perhaps sulfur and/or phosphorus are removed. The cleaned pyrolysis gas is then mixed with air and burned in the combustor before proceeding to the stack and any clean-up or heat recovery devices required.
A portion of the hot combustion gases are recycled from the combustor to the rotary kiln/heat exchanger to provide the heat for this vessel.

DIAGRAM:




STATUS: Modification of commercially-available process

ADVANTAGES: The volatilization/pyrolysis by the heat exchanger substantially reduces the duty on the halogen removal/clean-up device.
Recycling the flue gas minimizes the auxiliary fuel requirements.

DISADVANTAGES: Pyrolysis products not easily predicted
Possible difficulty in maintaining rotary kiln seal and seal at heat exchanger-kiln interface.

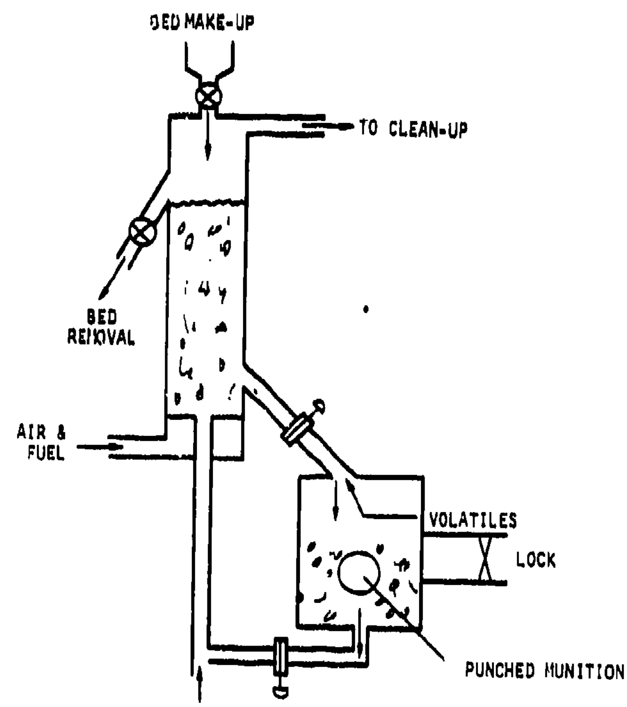
REMARKS: Worth further consideration

PROCESS NO. 32

FLUID BED (THERMAL DOWNLOAD)

DESCRIPTION: A conventional fluidized bed coupled with two or more batch fluid bed volatile chambers. Agent and auxiliary fuel burning in the fluidized bed reactor heat the bed material which is circulated at a controlled rate to one of the volatile chambers. The hot bed material volatilizes agent and explosives from a punched munition in the volatile chamber. The volatilized materials enter the fluid bed reactor by flowing upward against the hot bed material entering the volatile chamber. After 5X decontamination, the appropriate knife valves are closed and the second volatile chamber, containing fresh munition, is brought on line.

DIAGRAM:




STATUS: Conceptual

ADVANTAGES: Good waste heat utilization

Ease of removal of metal parts

DISADVANTAGES: Possible to remove some contaminated bed material when removing metal parts

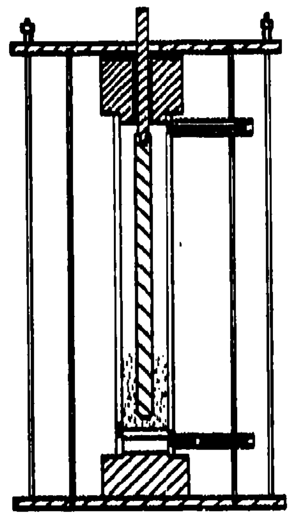
REMARKS: Worth further consideration

PROCESS NO. 33

RESISTANCE-HEATED FLUIDIZED-BEDS

DESCRIPTION: A conventional fluid bed in which electrodes in the bed or wall supply energy to an electrically-conductive bed material. Temperatures of up to several degrees Celcius can be achieved with upper limits being primarily a result of materials of construction. Hazardous materials can be either pyrolyzed or oxidized.

DIAGRAM:



STATUS: Experimental

DEVELOPER: Battelle

ADVANTAGES: High temperatures pyrolysis or oxidation
Smaller size requirements than in conventional incineration
Efficient energy usage (no energy wasted heating flue gases)
Low gas throughput requires smaller pollution control equipment

DISADVANTAGES: Materials compatibility problems (materials of construction and bed material) due to high temperatures
High operating costs

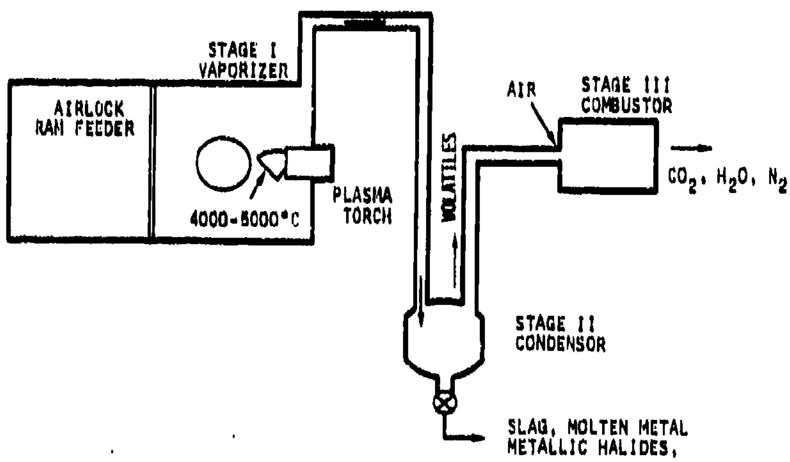
REMARKS: Worthy of further consideration

# PROCESS NO. 34

## PLASMA ARC VAPORIZER

DESCRIPTION: Munitions/items are fed through an airlock system into a plasma chamber (Stage I). Nitrogen is ionized to form a plasma with temperatures ranging between 4000 C and 5000 C. The high temperatures vaporize the entire munition/item completely disassociating the contained agent. The metallic vapors (phospides, sulfides, chlorides, and fluorides) are condensed in Stage II as molten metals and metallic halides, phosphides, and sulphides. In Stage III, the remaining vapors are mixed with air and combusted to $CO_2$ and $H_2O$.

FLOW DIAGRAM:




STATUS: Theoretical/experimental

MANUFACTURER: Westinghouse

ADVANTAGES:
Limited feedstock preparation
Reduced air pollution control requirements

DISADVANTAGES:
Principle unproven (conceptual)
High energy costs
Technology needed to produce metallic halides not yet established
Materials problems at high temperatures

REMARKS: Extensive development required and high costs are likely

PROCESS NO. 35

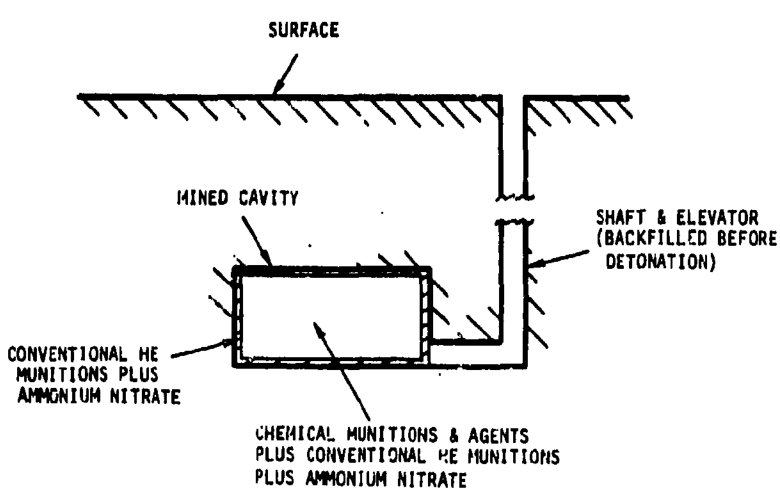
UNDERGROUND DETONATION

DESCRIPTION: A cavity is mined at a suitable depth in a suitable formation, chosen such that no venting to the surface will occur when a large quantity of explosive is detonated in the cavity. The cavity is filled with a mixture of conventional (HE) munitions awaiting demilitarization, ammonium nitrate (AN), and chemical munitions with agent containers. The loading is such that a "layer" of conventional munitions and AN lines the cavity, and a mixture of conventional munitions, AN, and chemical munitions/items fills the remaining space.

After backfilling the entrance shaft, the material is detonated by charges located at multiple points in the layer free of agent. This forms an initial zone of hot, high-pressure gas that prevents undecomposed agent from being driven into the cavity walls.

The mixture of conventional munitions, AN, and chemical munitions items is chosen to yield a sufficiently high temperature to decompose the agent (and optionally, sufficient excess oxygen to burn the agent to a specified degree of completeness) and sufficient shock pressure to insure that all chemical munitions have been broken open and all explosives in such munitions detonated.

DIAGRAM:



PROCESS NO. 35

UNDERGROUND DETONATION (continued)

STATUS: Conceptual

ADVANTAGES: No munition preparation required

DISADVANTAGES: Munitions/items would need to be transported to a site with suitable underground structure

Small-scale tests to determine feasibility or proper mixtures will be difficult to interpret

The chemical munition/item density will be low requiring a large cavity volume per item

Debris and decomposition products remain buried with no reasonable method of further processing

REMARKS: Worth further consideration

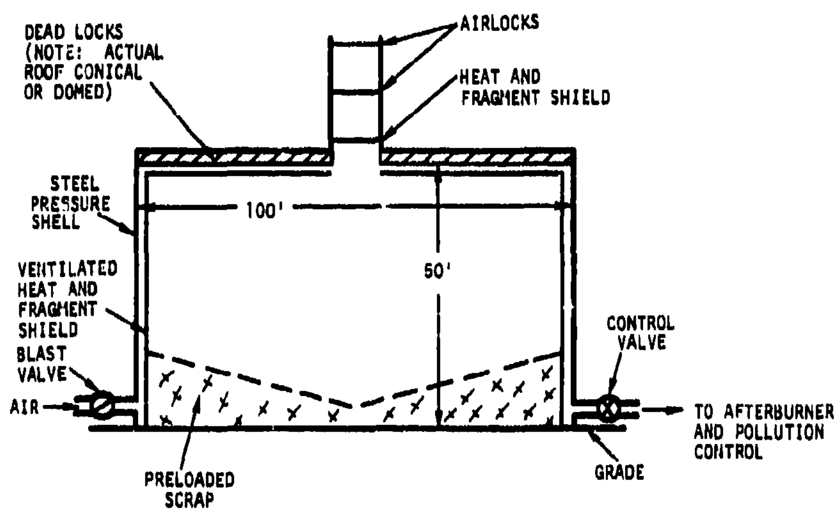
PROCESS NO. 36

VERY LARGE ENCLOSURE

DESCRIPTION: A fire is started in the enclosure. Packed munitions, agent containers, etc., are dropped into the fire through the air lock. Sufficient fuel value (agent, explosives, propellants, dunnage) is associated with the munitions and containers to maintain burning.

When accumulated scrap becomes excessive (possibly when the central pile becomes high enough to threaten the possibility of munitions rolling to the wall), munition/agent feed is terminated and burning is maintained by firing clean fuel for a period long enough to ensure explosion of any munition and vaporization or decomposition of any agent. After a cooling period, the locks are opened and scrap removed (possibly by a clam shell). The fire is then restarted and feed resumed. Scrap can be 5X decontaminated in a conventional furnace.

DIAGRAM:




STATUS: Conceptual

ADVANTAGES: Capable of processing all-up munitions

DISADVANTAGES: Airlock and fragmentation shields are difficult to design
Simultaneous processing of a large number of munitions increases hazards

REMARKS: Worth further consideration

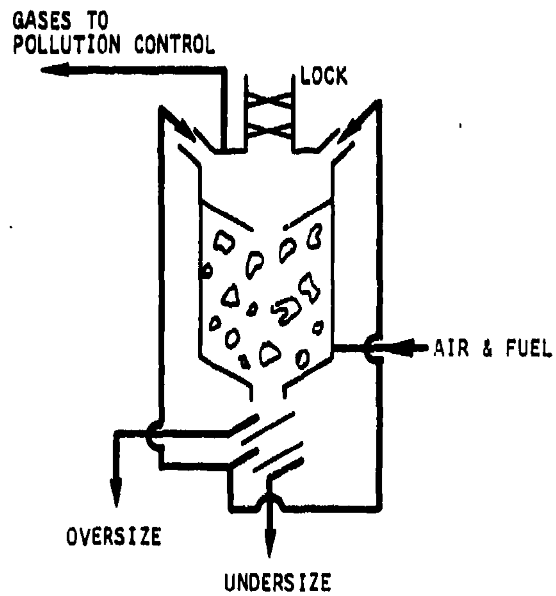
## PROCESS NO. 37

## SHAFT FURNACE/SCRAP CYCLE

DESCRIPTION: Unpacked munitions are fed with recycled scrap to a shaft furnace. The feed is arranged to cause the munitions to be approximately at the shaft centerline. The munition is heated as it descends and eventually explodes as a result of increased internal pressure caused by agent volatilization or explosive detonation.

The surrounding scrap stops fragments and attenuates the blast wave, reducing the containment capability required of the wall. Released agent burns contributing heat. Scrap is discharged, cooled, screened for oversize and undersize, and recirculated. The scrap recirculation rate is high compared to the munition feed rate.

DIAGRAM:




STATUS: Conventional

ADVANTAGES: Munitions explosions are acceptable

DISADVANTAGES: Design requirements for vessel must be determined accounting for blast containment, static/dynamic overpressure containment, allowable wall temperature, internal refractory, feed and discharge locks, gas inlet and outlet locations, interaction between inlets and exits during surges and backflow

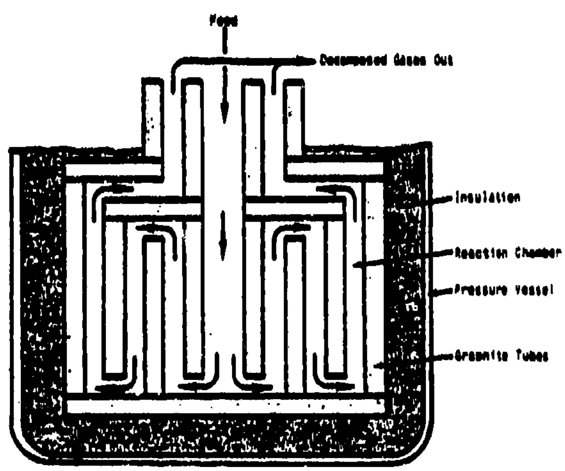
REMARKS: Worth further consideration

PROCESS NO. 38

# STEAM PYROLYSIS
# (SEGAS)

DESCRIPTION: A continuous, non-catalytic stream reformation process in which steam is contacted with hydrocarbons at high temperatures (1227 C) over relatively long retention times. The reactor used (see diagram) is a pressure vessel with an array of tubes inserted in order to lengthen the reaction path. The reactants can be heated either electrically or by burning a portion of the product gas. Careful selection of the materials of construction of the reactor is necessary when the fuel is the product gas. Graphite or silicon carbide tubes are used as the heating elements in electrically-heated reactors.

DIAGRAM:




ELECTRICALLY-HEATED SEGAS WASTE DESTRUCTION REACTOR

STATUS: Laboratory scale

PREVIOUS APPLICATIONS: PCB destruction

PROPRIETOR: A. L. Sandpiper Corporation

COST: Assuming a feed rate of 600 gal/hr of pure PCB, costs were estimated to be:

| | |
|---|---|
| Capital | $2.44 M |
| Operating | $0.41/gallon of waste liquid feed |

PROCESS NO. 38

STEAM PYROLYSIS PAGE 2

ADVANTAGES: Simple reactor construction

DISADVANTAGES: Possible materials compatibility problems

REMARKS: Limited application but worth further consideration

PROCESS NO. 39

INSITU PYROLYSIS/OPEN CAVITY

DESCRIPTION: Pyrolysis of agent within the munitions and bulk containers. The concept involves the placement of nonburstered/deburstered munitions into a heated chamber. The heating chamber would be sealed and purged with nitrogen, so that palleting materials would not burn. The chamber would be heated above the decomposition temperature of the agent and held at that temperature to insure agent destruction. In order to prevent agent cavities from rupturing due to the increase in internal pressure during heating, an expansion volume container is attached to the cavity. The container allows the gases to expand and not cause vessel rupturing. The concept would require munition unpacking and accessing of the agent cavity for those configurations which could not withstand the internal pressures (mines, rockets, bombs, spray tanks, mortars, and ton containers).

STATUS: Conceptual

ADVANTAGES: No pollution control required

DISADVANTAGES: Pallets may lose the ability to support munitions/items after pyrolysis

Munitions/items which could not withstand internal pressures would have to be unpacked

Enclosed explosives, fuzes, propellants would have to be removed since high temperatures and pressures would lead to detonation

# PROCESS NO. 40

## INSITU PYROLYSIS/CLOSED CAVITY

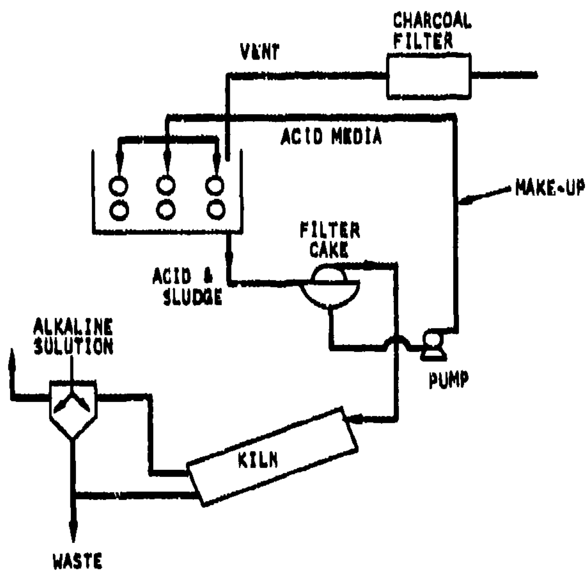
| | |
|---|---|
| DESCRIPTION: | Pyrolysis of agent within the munitions and bulk containers. The concept involves the placement of nonburstered/deburstered munitions into a heated chamber. The heating chamber would be sealed and purged with nitrogen, so that palleting materials would not burn. The chamber would be heated above the decomposition temperature to insure agent destruction. In order to prevent agent cavities from rupturing due to the increase in internal pressure during heating, the chamber pressure would be cycled to match the munitions' internal pressure as it is heated or cooled. |
| STATUS: | Conceptual |
| ADVANTAGES: | No pollution control required |
| | Minimum feedstock preparation requirements |
| DISADVANTAGES: | Pallets may lose the ability to support munitions/items after pyrolysis |
| | May be difficult to match cavity and chamber pressures if cavity pressures are not monitored |
| | Enclosed explosives, fuzes, propellants have to be removed since high temperatures and pressures would lead to detonation |
| | After pyrolysis and cooling, the agent cavity would still be under pressure due to decomposition products |

PROCESS NO. 41

ACID DISSOLUTION/INCINERATION

DESCRIPTION: All-up munitions are placed in an acid-proof vat and acid solution is pumped over them, dissolving the metal. Resultant sludge is filtered and incinerated. When dissolution is "complete", residue (explosive, undissolved metal) is dredged from the vat and incinerated. Released agent is dissolved, hydrolyzed, and incinerated. Acid recovery may be practical. Incineration can be performed in a rotary kiln, molten salt bath, molten metal bath, or wet-air oxidation unit.

DIAGRAM:




STATUS: Conceptual

ADVANTAGES: Pollution control requirements can be reduced if acid can be recovered and molten salt bath, molten metal bath, or rotary kiln with limestone feed can be used for incineration step

DISADVANTAGES: Dissolution rate not known, and if slow, required vat size may be excessive

If acid cannot be recovered, extensive waste treatment required

Effect on fuzes unknown

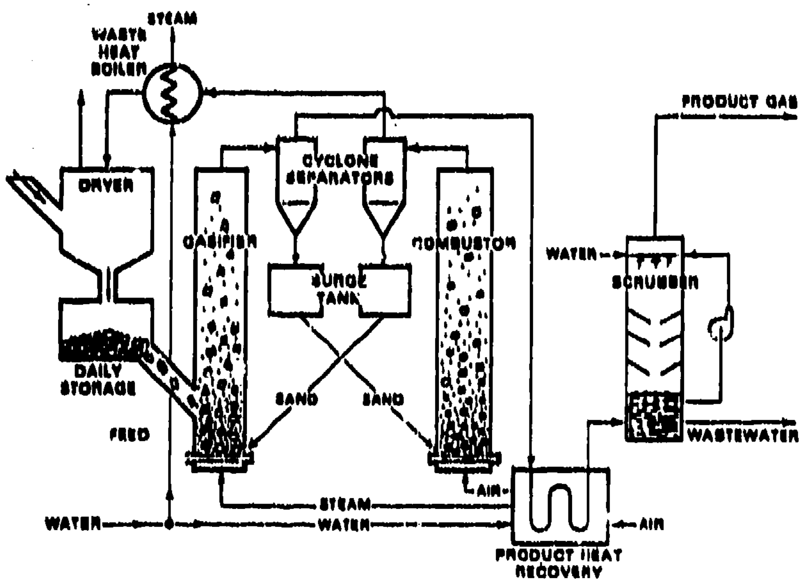
REMARKS: Worth further consideration

PROCESS NO. 42

# MULTI-SOLID FLUIDIZED BED (MSFB)

DESCRIPTION: Fluidized bed with the ability to fluidize coarse particles that are usually not fluidizable. Fluidization takes place in a flowing gas/solids suspension. With coarse particles fluidized, the backmixing of the fluidized bed and the collisions between the entrained solids in the gas/fine solids suspension and dense phase fluid-bed particles result in a greatly increased residence time for the entrained solids.

DIAGRAM:




SIMPLIFIED PROCESS FLOWSHEET--MSFB WOOD GASIFICATION COMMERCIAL DESIGN

STATUS: Pilot scale/commercial

PROPRIETOR: Battelle

ADVANTAGES: High throughputs achievable

High fluid-bed density and vigorous mixing make the MSFB relatively insensitive to the properties of the feed material

High rates of heat and mass transfer have been achieved

Solids distribution is simplified because of high velocities and vigorous mixing

High potential for waste heat utilization

PROCESS NO. 42

MULTI-SOLID FLUIDIZED BED 

DISADVANTAGES: Complexity of oepration

REMARKS: Worth further consideration

# PROCESS NO. 43

## VACUUM FURNACE

DESCRIPTION: A furnace run at an absolute pressure of approximately 0.1 atm and having 100 cu ft of volume per pound of explosive and propellant. The large volume and reduced pressure prevent chamber pressure from exceeding one atmosphere during rapid burning of the explosive. Enough air leaked into the chamber to burn agent as it evaporates out of munition. The furnace can be heated by either infrared or induction heaters. The walls of the chamber should be kept warm to prevent the condensation of agent or combustion products.

Since the Nash Pump is a constant volume pump, the time in the afterburner should be independent of pressure and set by the afterburner volume and pump capacity rather than agent release rate. Steam ejectors can also be used as a vacuum source.

STATUS: Conceptual

ADVANTAGES: Explosives do not detonate under reduced pressure

The Nash pump can serve as a scrubber

The agent cavity may not need to be opened since heating could evaporate agent and burst cavity

DISADVANTAGES: High potential for materials compatibility problems

REMARKS: Extensive development required

# PROCESS NO. 44

## INDUCTION FURNACE

DESCRIPTION: A fume incinerator in which energy required to promote oxidation is supplied by preheated air instead of by combustion of an auxiliary fuel or ignition of the fume itself with a pilot. Air is preheated as it passes over induction coils before entering mixing chamber (fume incinerator).

STATUS: Experimental/bench-scale

DEVELOPER: Midland-Ross

ADVANTAGES: Induction heating offers a means of rapid heating and possible increased production rates

Less carbon dioxide generated reducing the salt generation in the scrubber

DISADVANTAGES: Energy conversion efficiency less than in an IR furnace

Possible cold walls could lead to agent and/or tar condensation

The following are concepts or processes which were not included in the evaluation as separate items because they had no significant benefits over a concept evaluated or were included as part of a concept evaluated.

## Multiple Hearth Furnace

Hearth furnaces are typically used to incinerate sludges and normally operate in a counter-current flow mode. An IR furnace that has been evaluated is a modified hearth furnace. Other hearth furnaces appear to offer no advantages over rotary kilns and typically have higher capital and operating costs.

## Laser Systems

The present application of laser technology is as a UV photolysis process. This appears to be very expensive hardware to be used as a UV source and other utilization of the laser does not seem feasible.

## Microwave Plasma

This technology is similar to plasma arc but is not as well-developed. There does not appear to be a significant benefit in using a microwave instead of an electric arc to generate the plasma.

## Lime Kiln

Lime kilns all fall under the following categories: shaft furnaces, rotary kilns, rotary hearths, and fluidized-beds. These have been evaluated independently.

## Glass-Melting Furnace

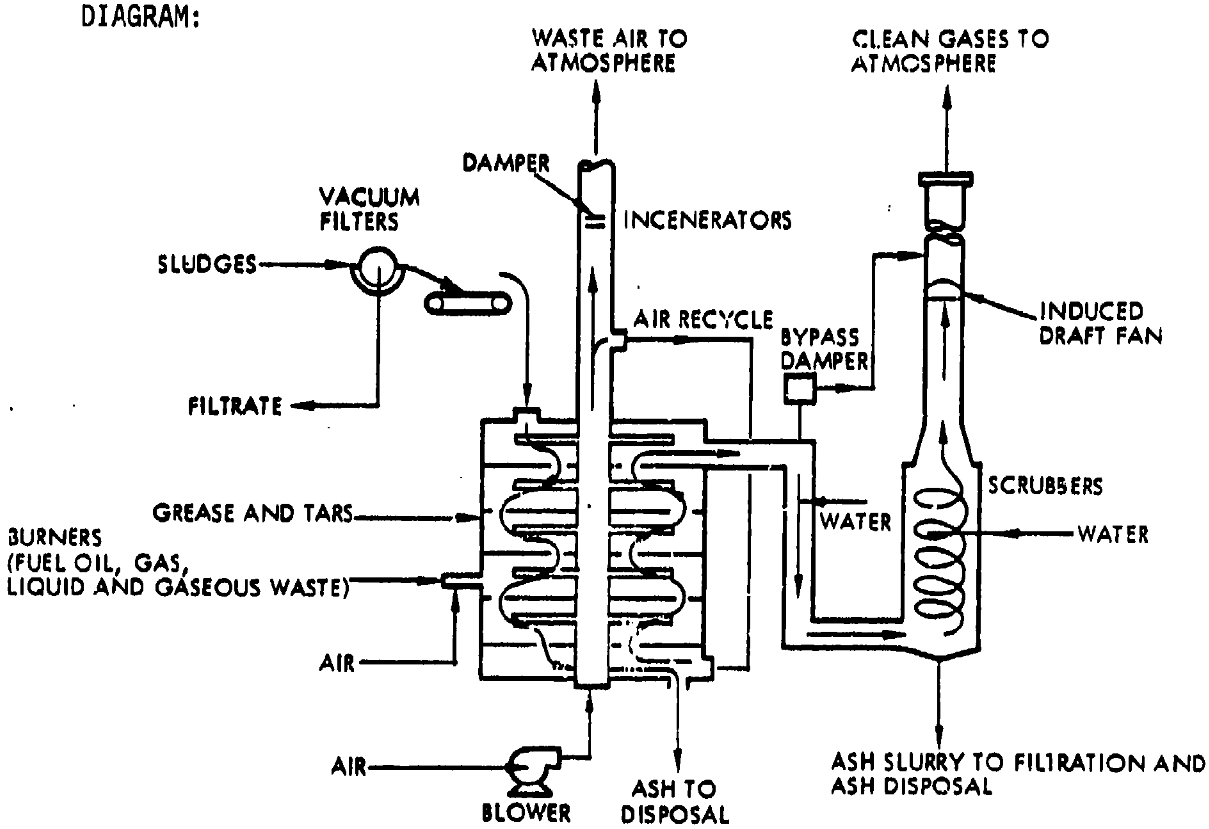
This technology is the same as molten salt and molten metal and is incorporated in those evaluations.

Detailed descriptions of these concepts follow.

MULTIPLE HEARTH

DESCRIPTION: A refractory-lined steel cylinder divided into smaller chambers by self-supporting refractor arches. A central shaft with horizontal arms plows waste along refractor arch to drop-opening where wastes fall into next chamber. The wastes fall through successive chambers and ash is removed at bottom of the furnace. Fuel and air are introduced through a port on the side of the furnace and combustion gas flow countercurrent to wastes. Liquid and gas wastes can be incinerated by injection through burner nozzles.

DIAGRAM:




STATUS: Commercially available

PREVIOUS APPLICATIONS: Sewage, sludges, tars, liquids, gases

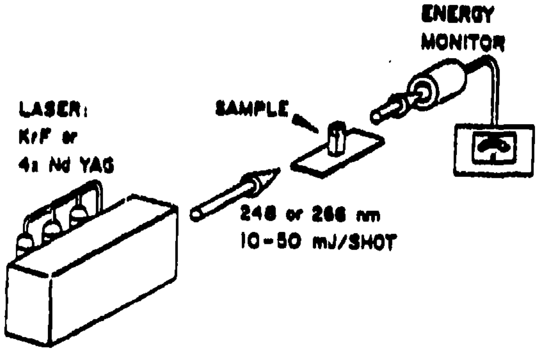
MULTIPLE HEARTH (continued)

| | |
|---|---|
| ADVANTAGES: | High residence times<br>Desired temperatures profiles can be maintained by addition of fuel burners to various hearths<br>High fuel efficiency is achieved in the multizone configuration<br>A wide variety of wastes can be incinerated |
| DISADVANTAGES: | Moving parts and associated maintenance and maintenance costs<br>Susceptible to thermal shock resulting from feed interruptions<br>High capital cost<br>Possibility of partially-combusted materials to exit with ash<br>High fuel and air consumption are typical<br>Countercurrent flow |
| EVALUATION: | A secondary combustion chamber would be required for hazardous wastes<br>Limited application |

## LASER

DESCRIPTION: The irradiation of wastes with ultraviolet light supplied by a laser.

DIAGRAM:




STATUS: Experimental

PREVIOUS APPLICATIONS: GB, VX

DEVELOPER: Los Alamos Scientific Laboratory, University of Pittsburgh

ADVANTAGES: Light energy (photons) can be delivered at higher rate than with conventional processes, thus increasing the rate of hazardous chemical compound destruction or catalyzation. Range of wavelengths emitted can be limited to narrower regions if desired.

DISADVANTAGES: High capital cost (higher than other means of UV irradiation)

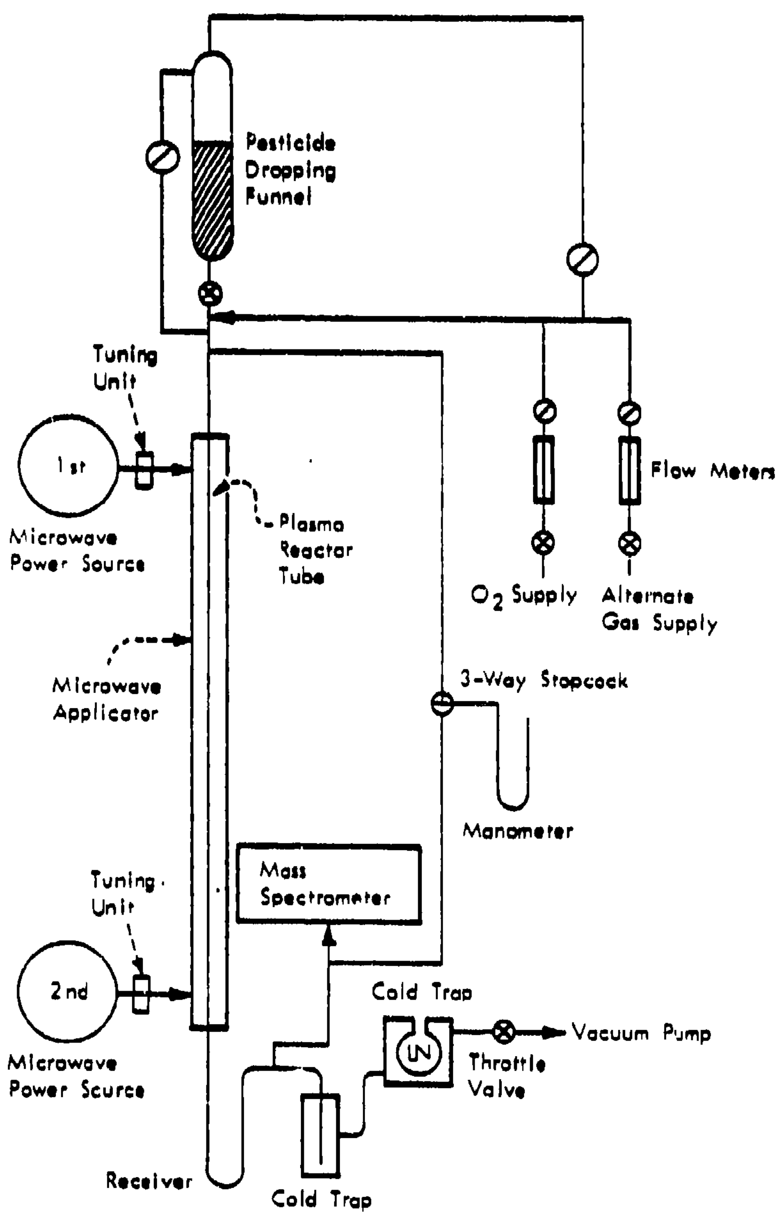
Higher operating cost due to inefficient energy conversion associated with laser

EVALUATION: UV pyrolysis with the expensive laser as the source

# MICROWAVE

DESCRIPTION: Destruction of wastes in a thermal plasma energized by a microwave material (liquid, slurry, solution in water, compressed cake or pellet) is fed into reaction chamber (silica or quartz) with a carrier gas. The carrier gas is ionized and the microwave-induced electrons react with neutral organic molecules to form free radicals which ultimately dissociate or react with oxygen to form simple reaction products.

DIAGRAM:



MICROWAVE (continued)

| | |
|---|---|
| STATUS: | Bench-scale/prototype |
| PREVIOUS APPLICATIONS: | Pesticides, PCBs, nerve poisons, organometallic compounds |
| DEVELOPER: | Lockheed Missiles and Space Company |
| ADVANTAGES: | Low cost<br>High destruction efficiencies predicted<br>Metal fumes are less likely to cause problems than in other high-temperature processes |
| DISADVANTAGES: | Plasma reaction products are unpredictable and can be toxic<br>Oxygen must be used as carrier gas to insure complete combustion of wastes and prevent the formation of additional toxins<br>Extensive development required<br>No known work being performed in the area at present time |
| EVALUATION: | Essentially plasma pyrolysis with a different energy source |

# LIME KILNS

DESCRIPTION: The calcination process to produce lime has been performed in rotary kilns, vertical shaft kilns, rotary hearth furnaces, and fluidized-beds. The calcination process involves the burning of calcium carbonate to form lime:

$$CaCO_3 \rightleftharpoons CaO + CO_2$$

Vertical shaft kilns have been used to produce lump lime and rotary kilns have been used to produce fine lime. Highly-reactive lime has been produced in fluidized-beds and rotary hearths.

In vertical kilns, crushed limestone is dropped into the top of the kiln and is calcined as it falls. Vertical kilns are fired either by burning a mixed feed of coke and limestone or by burning oil or gas. The more sophisticated and higher capacity vertical shaft kilns are oil- or gas-fired.

Rotary kilns used in lime calcination are commonly 150 feet long but have extended to lengths of up to 400 feet with 11 feet diameter.

In the rotary hearth calciner, limestone is dropped onto a slowly-rotating disk that serves as the furnace bottom. Combustion air and fuel are fired into the kiln tangent to the side walls and above the limestone bed. A vortex is formed as hot combustion gases move upward toward the stack. After one complete revolution, the waste is plowed off the disk and exits through a drop hole.

STATUS: Commercial

ADVANTAGES: Capture of acidic pollutants by lime

DISADVANTAGES: Commercial units too large and have higher capital cost than necessary.

EVALUATION: Repeat of conventional technology plus a reactive medium

# GLASS MELTING FURNACES

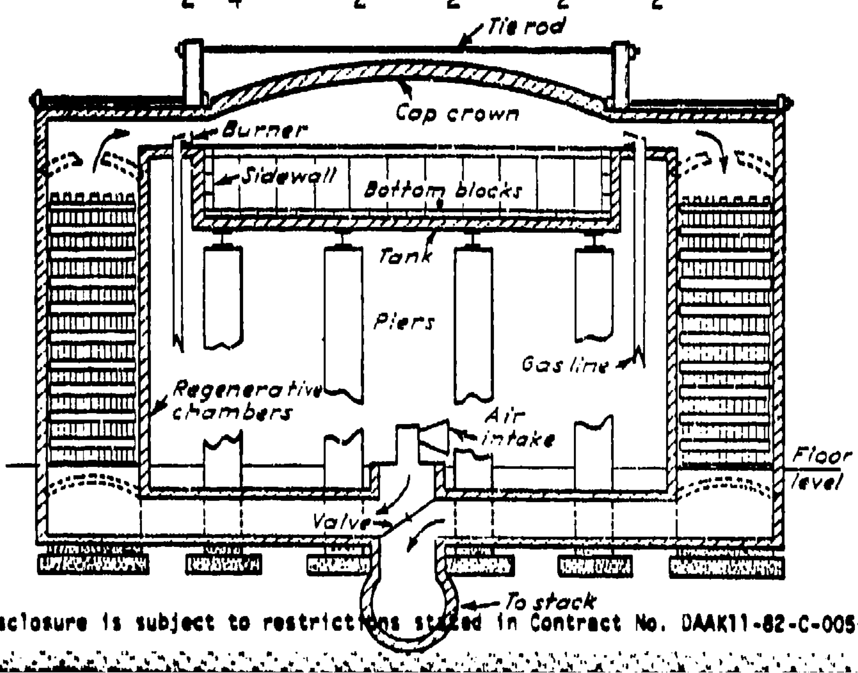
DESCRIPTION: Small-scale manufacture of glass is performed by melting the raw materials in crucibles or pots containing from one to two tons of glass. The crucibles are heated batchwise in large furnaces. Large-scale manufacture is performed either batchwise or continuously in large, enclosed furnaces that are lined with refractory brick. The heat necessary for melting the glass can be supplied by burning fossil fuels over the surface of the glass, by electrodes which project from the furnace walls into the melt, or by a combination of the latter two techniques. In continuous processing, the raw materials are charged into the melting furnace and, after melting, pass through a narrow passage (throat) to the refining section where gases escape from the melt. Regenerative firing is commonly practiced when heat is supplied by combustion. In regenerative firing, the flow of combustion air and flue gases is reversed every 15 to 30 minutes to take advantage of sensible heat stored in brick lattices (checkers) and preheat intake air. The major raw materials are sand, soda ash, and limestone or lime. The following chemical reactions are involved:

$$Na_2CO_3 + aSiO_2 \rightarrow Na_2O \cdot aSiO_2 + CO_2$$

$$CaCO_3 + bSiO_2 \rightarrow CaO \cdot bSiO_2 + CO_2$$

$$Na_2SO_4 + cSiO_2 \rightarrow Na_2O \cdot cSiO_2 + SO_2 + CO$$

DIAGRAM:



GLASS MELTING FURNACES (continued)

| | |
|---|---|
| STATUS: | Commercial |
| ADVANTAGES: | Capture of pollutants in glass melt |
| DISADVANTAGES: | Commercial units may be too large and have high capital cost |
| EVALUATION: | Essentially a molten salt process |

# APPENDIX D

## ENGINEERING AND ECONOMIC ANALYSIS - ACID ROASTER

# APPENDIX D

## ENGINEERING AND ECONOMIC ANALYSIS - ACID ROASTER

### Engineering Analysis

The state of the art technology for destroying hazardous liquids is liquid injection incineration. In the acid roaster process concept, the items/munitions in lethal agent inventory are converted to a feedstock suitable for liquid injection incineration by treating them with hydrochloric acid. The sequential processing steps are illustrated in Figure D-1 by a process flow chart. The thermal process equipment receives the munition and items from the mechanical preparation area as whole munitions/items separated from the non-metal dunnage (feedstock configuration b). The whole munition/items are placed in dissolution tanks where they are contacted with flowing hydrochloric acid which sequentially dissolves the munition body, washes out, mixes and possibly reacts with the agent, dissolves the fuze and burster well, and then degrades the energetic materials (explosives and rocket propellants). The acid and the products of dissolution are collected in the bottom of the tank (ground if necessary) and then pumped as a slurry to a liquid injection incinerator or roaster where the agents and/or their hydrolysis products are thermally destroyed, the degraded energetic materials combusted, the water and excess acid evaporated, and the metallic salts roasted. The separated dunnage is also fed to the roaster where it is combusted contributing to the heat duty of this unit. The solid residues leave the roaster in a 5X decontaminated form that is suitable for landfilling and has a high potential for reuse. The hot gas stream from the roaster passes through an afterburner which provides redundancy in agent destruction capability, and then enters an acid recovery unit similar to those used by the steel industry in steel pickling plants[1,2,3]. The acid recovered in this unit is recycled to the dissolution tanks and the gaseous effluent is sent to a spray dry

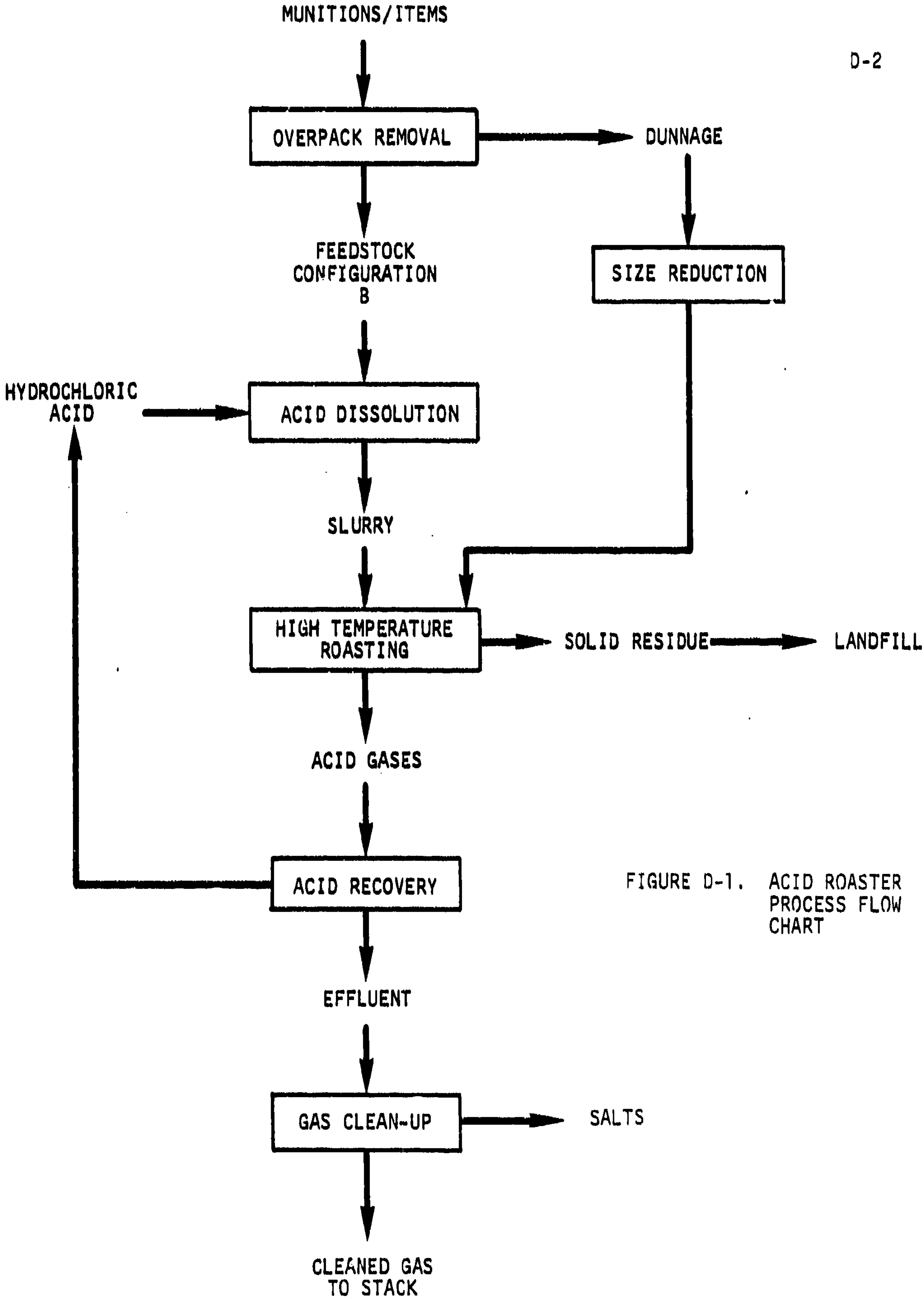



FIGURE D-1. ACID ROASTER PROCESS FLOW CHART

scrubber and baghouse for final cleanup of the acid gases before being vented to the atmosphere through an induced draft fan. The concept and the required hardware are discussed in more detail below.

## A. System Concept Description

The Acid Roaster Process is made up of the following four systems:

- Dissolution System
- Roaster/Afterburner System
- Acid Recovery System
- Pollution Abatement System.

A detailed description of each of these four systems as well as a detailed energy and material balance for a 400 lb/hour agent throughput are given below. Additional details associated with scaling the process for other agent throughputs can be found in the Economic Analysis section of this appendix.

A-1. Acid Dissolution System. Using acid to dissolve and provide entry into metallic bomb cases is the basis of acid trepanning, technology that has been in existence for several decades[4,5] and is currently utilized by the Naval Explosive Ordnance Disposal Technology Center. In this concept, complete dissolution of the metal parts rather than simple entry of the explosive cavity is required. The magnitude of the demilitarization program instills the added desires to reduce the costs associated with both acid use and environmental cleanup. For these reasons, use of a hydrochloric acid is preferred over the nitric acid systems normally used in acid trepanning.

To determine the time required to dissolve the munition bodies, and thereby determine the needed size and quantity of dissolution tanks, it was first necessary to determine the rate at which hydrochloric acid will dissolve steel. A review of the available literature[6,7,8,9] indicates that a quiescent solution of

20 percent hydrochloric acid in water at a temperature of 85°C will penetrate steel at an average rate of 0.042 inch/hour. These sources also indicate that the dissolution rate of aluminum rocket bodies would be greater than steel. This rate data was used as the basis for the dissolution tank design. However, the literature also indicates that a flowing system and the presence of ferric chloride in the solution will markedly increase corrosion rates[9,10] Calcott reported a five-fold increase in the acid dissolution rate when the acid velocity was increased from 0 to 9 feet/minute. Since the munition bodies will be dissolved by a flowing hydrochloric acid system that also will contain dissolved ferric chloride, use of the available quiescent solution rate data would lead to a conservative design.

The second determinant of the dissolution time is the thickness of the metal being dissolved. Review of the munition/item descriptions[11] indicate that the thickest metal parts in the inventory are in the 8-inch projectile. At its thickest point, the casing for this munition is 0.95 inches thick with 90 percent of the casing less than 0.625 inches thick. The next thickest item (155-mm projectile) is only 0.625 inches at its thickest point. While initial dissolution of the items will take place only on the outer surfaces, once the cavity has been penetrated and the agent drains out, the inner surface will be subject to attack which could conceivably double the surface area available for dissolution.

Based on the above discussion, the following conservative assumptions were made during the design estimations:

- The munition/item casings are uniformly one inch thick
- The dissolution rate of steel in the acid stream is 0.042 inches/hour
- Once the munition has been penetrated exposing a greater surface area, a slight reduction in the acid concentration would be acceptable

The dissolution system was therefore designed on the basis that the munition bodies would dissolve in 20 hours.

Since grinding and pumping of slurried explosives is accepted practice in the munitions industry, the dissolution system is not being designed for blast containment. Experience in this industry indicates that as long as the liquid velocity and temperatures are maintained at levels adequate to prevent the settling or condensation of slurried or dissolved explosives propagation of an explosion through the piping is not possible.

Dissolution Tanks. The dissolution tanks will be rubber-lined, carbon steel tanks similar to those used in electroplating. The tanks will be completely sealed with an access door in one end. The entire tank will be further enclosed within a ventilation hood to prevent hydrogen leakage. The number and size of tanks that are required by the concept is determined by the following consideration:

- Three equal batteries of tanks will be provided; one being loaded during each shift of operation while the other two are processing munitions.
- The required processing rate of munition/items needed to supply the desired agent throughput
- The maximum physical dimensions of the inventory items
- The need to assure uniform acid distribution
- The assumption that a fully loaded tank would have a void fraction of 50 percent with a 6-inch buffer space between the munition and the tank sides.

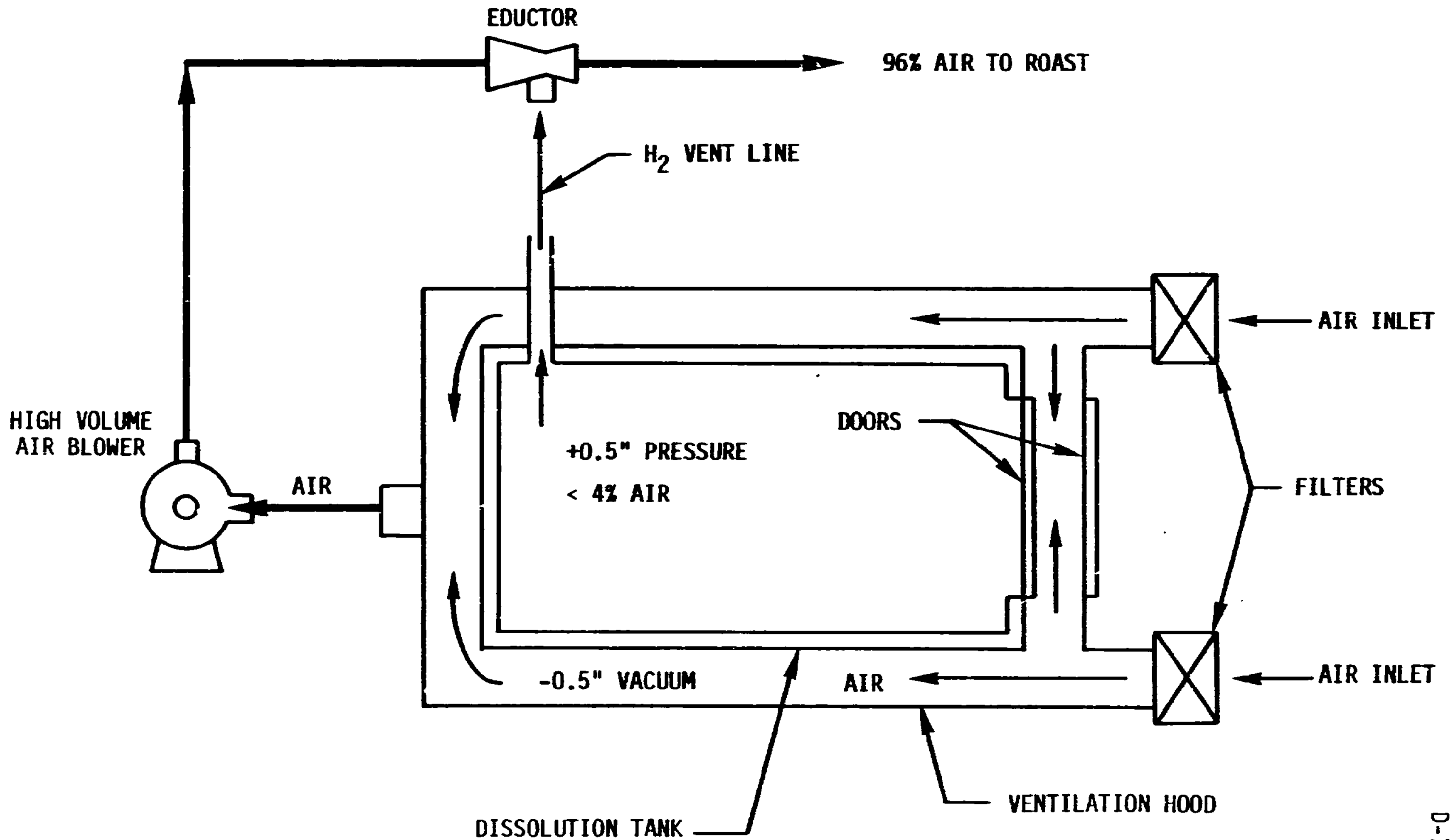
To assure that uniform acid distribution will be provided to the munition/items at all times, the dissolution tanks are limited to a depth of 6 feet. The minimum length of all tanks is fixed at 16 feet in order to accommodate the spray tanks. The minimum width of the dissolution tanks was fixed at 6 feet in order to hold two ton containers simultaneously. A maximum width of 16 feet was selected in order to limit the weight of munitions a reasonably constructed tank must support. The number of tanks required for a given agent throughput was then determined by these geometric restrictions and the volume of the various munition/items that would provide the agent capacity. For example, at a throughput of 400 lb/hr of agent, three 6-foot wide

tanks are required while at 5000 lb/hr of agent, fifteen 16-foot wide tanks are utilized.

Acid Distribution System. The acid distribution system consists of the pumps, spray nozzles, and plumbing required to move the acid solution to its destinations. This system is constructed entirely of acid resistant materials such as plastics, graphite, and titanium. Each dissolution tank has two pumps in parallel, one in operation and one in standby. This arrangement permits maintenance or replacement without interrupting service. A second set of pumps, again with parallel redundancy, serves to pump a used acid stream to the incinerator/roaster for destruction of contained agent and energetic materials as well as reclamation of the acid. All acid pumps are specified as centrifugal types, constructed of palladium stabilized titanium to be corrosion resistant. From the pumps, the acid is transported to its destination in acid resistant plastic pipe. Acid which is recycled directly to the dissolution tank first passes through a graphite heat exchanger which removes the excess heat of dissolution from the stream. (It should be noted that dissolved explosives could plate out in this heat exchanger and blast containment might be required for this component.) The recycled acid mixes with a stream of reclaimed acid before entering the dissolution tank via acid resistant spray nozzles. The nozzles are designed to assure uniform distribution of the flowing acid stream across all munition items in the tank.

Ventilation System. The ventilation system is represented graphically in Figure D-2. The dissolution of steel munition items by acid will release hydrogen gas as a by-product. Operation of the tanks at 80$^{\circ}$C will volatilize small quantities of agent, hydrochloric acid, and water vapor as well as gases from the possible decomposition of the energetic materials. Purging the tank with air at a negative pressure to safely eliminate these gases would markedly increase the acid carryout. Therefore, to remove these gases and avoid the hazards

FIGURE D-2. DISSOLUTION TANK VENTILATION SYSTEM



of handling hydrogen, the dissolution tank will be allowed to fill with the gaseous products of dissolution and operate at near ambient pressure. To prevent the influx of air into the dissolution tank and to immediately remove and dilute any hydrogen containing gases that might leak out of the tank, the hood surrounding the dissolution tank will be reduced to -5 inches water pressure and purged with a high volume of air. The gases will then be withdrawn from the tank, diluted with air at a ratio of greater than 24/1, and transported to the roaster by an air eductor. The blower that evacuates the hood also provides the air that operates the eductor. The ventilation system will thus convey the gaseous products from the dissolution tank to the roaster for safe destruction. In this manner the air/hydrogen mixtures ratios are kept above the hydrogen/air explosion in the tanks and below this limit elsewhere.

Roaster/Afterburner System. While acid hydrolysis of some agents may occur in the dissolution system, the roaster/afterburner is the system that is ultimately responsible for agent destruction. This system consists of a roasting chamber and an afterburner chamber as serial parts of a single unit. It is a carbon steel unit lined with acid resistant fire brick. Conventional oil-fired burners provide temperature control of both chambers.

Roasting Chamber. Liquid injection incineration and conventional roasting differ only in the location in which the stream to be processed is injected. In roasting, the process stream is normally sprayed into the hot gases at the exit of the unit permitting counter current flow to dry and oxidize the salts. The operating temperature is kept low to reduce fuel costs and promote the growth of large oxide crystals. Liquid injection incineration utilizes concurrent flow. The liquid to be destroyed is injected directly into the flame frequently with or in place of the fuel promoting a well stirred reactor zone at the inlet. The downstream reaction zone is kept as a plug flow reactor in which the operating temperature and residence time are

kept sufficiently high to assure complete combustion of the material being processed. Since agent destruction is the primary function of this unit, corrosion resistant nozzles will spray the process stream directly into the fuel oil flame near the bottom of the roaster and the unit will operate at downstream conditions that are severe enough to assume agent destruction (nominally 1600$^{o}$F for 2 seconds). To permit additional residence time at temperature for the salts to roast as well as to serve as method to burn dunnage, a small stoker grate is incorporated in the bottom of this unit. The burning of the dunnage as well as the hydrogen gas vented from the dissolution system in the roaster substantially reduces the fuel oil requirements of this unit. The majority of iron salts that have been roasted and the ash from the combusted dunnage will exit the bottom of this unit. In steel pickling operations, this stream of iron oxide is pure enough to be used in magnetic tape production and in fact, competes favorably with oxides from other sources. While the incorporation of wood ash as well as iron salts of phosphorus, fluorine, and/or sulfur may preclude this market, the residue should meet RCRA standards for landfilling and could have a significant resale value.

Afterburner. The afterburner is simply an additional incineration chamber located directly above the roasting chamber. Its purpose is to provide temperature and residence time redundancy to prevent accidental release of agent. A smaller quantity of reclaimed acid is injected at the top of the afterburner to cool the flue gas to protect downstream process equipment. A small carbon steel cyclone is also attached to the flue gas outlet to remove entrained solids. This cyclone is externally heated to keep its walls above 300 C to prevent corrosion by condensed acid gases.

Acid Regeneration System. The acid regeneration system is adapted from the design of regeneration plants that have been commercially available from Dravo Engineers Incorporated for approximately 20 years[12]. The emphasis of the design of this equipment is the

production of a high concentration acid stream ( 20 percent) without regard to the quantity of acid gases in the effluent. It therefore represents a worst-case pollution abatement scenario for evaluating the acid roaster concept for demilitarization applications and as such, has been incorporated in the concept design It is anticipated that, when more is known about upstream processes, the concept can be refined to reduce the pollution abatement needs.

The gaseous effluents from the roaster/afterburner first pass through two heat exchangers of titanium construction where they are cooled to saturation temperatures. They then pass into an isothermal absorber constructed from graphite where acid gases are condensed in the presence of liquid water. The uncondensed gases leave the absorber and proceed to the bottom of an adiabatic scrubber. The liquid stream is mixed with makeup acid and pumped to the top of the adiabatic scrubber. In the scrubber, which is constructed of fiberglass materials, the rising gas stream from the absorber is brought back into contact with the acid stream from the absorber which strips most of the remaining acid from this gas. The regenerated acid stream leaving the adiabatic scrubber has an acid concentration of 20 percent and is then, with the exception of a small bleed stream to the afterburner, pumped back to the dissolution system for reuse. The gaseous effluents from the adiabatic scrubber are warmed in a pass through a final heat exchanger which warms the gases above the dewpoint before being vented to the pollution abatement system.

Pollution Abatement System. The pollution abatement system consists sequentially of a spray dry scrubber where remaining acid gases are removed by sodium hydroxide; a baghouse which removes any suspended particulates from the gas stream; an induced draft fan that maintains the entire process under negative pressure and assures the smooth flow of gases; and a stack through which the gaseous effluents are emitted to the atmosphere. Since the recovery unit effluent has been warmed above the downpoint, the scrubber can operate as a dry unit. As such, it is baseline technology and needs no further description.

Energy and Material Balance. The concept described in the above narrative, is represented graphically in Figure D-3 by a process flow diagram. An energy and material balance was performed by computer simulation around the major pieces of equipment in order to produce the listing of stream temperatures and compositions summarized the computer printout in Table D-1. This balance was based on the operating constraints discussed previously, the assumption that the processing rate would be 400 lb/hr of GB, and the Army guidelines concerning the quantities and, when appropriate, heats of combustion of the accompanying dunnage, metal, and explosives. Thermodynamic data available in the literature were used to compute the stream compositions in the $HCl-H_2O$[13], $HF-H_2O$[13], and $HCL-FeCl_2$, $H_2O$[14,15] equilibrium systems.

## B. System Feed Requirements

As stated previously, this concept is designed to process feedstock configuration b. In designing for this configuration, it was assumed that when the unpack area separated the item/munitions from their packing, they were cleaned which is assumed to include removal of grease and removal of paint from all items and, in addition, removal of the fiberglass sheath from the rockets. It was further assumed that the items were placed on reusable fiberglass pellets that permit the use of mechanical devices in loading the dissolution tanks (e.g., fork trucks).

## C. Pollution Abatement System

There are no liquid effluents from this process. As discussed in the concept description, the only gaseous effluent is treated with the baseline spray dry scrubber technology. While the concentration of acid gases being removed from this stream is appreciably higher than the baseline, this is not expected to produce additional technical problems.

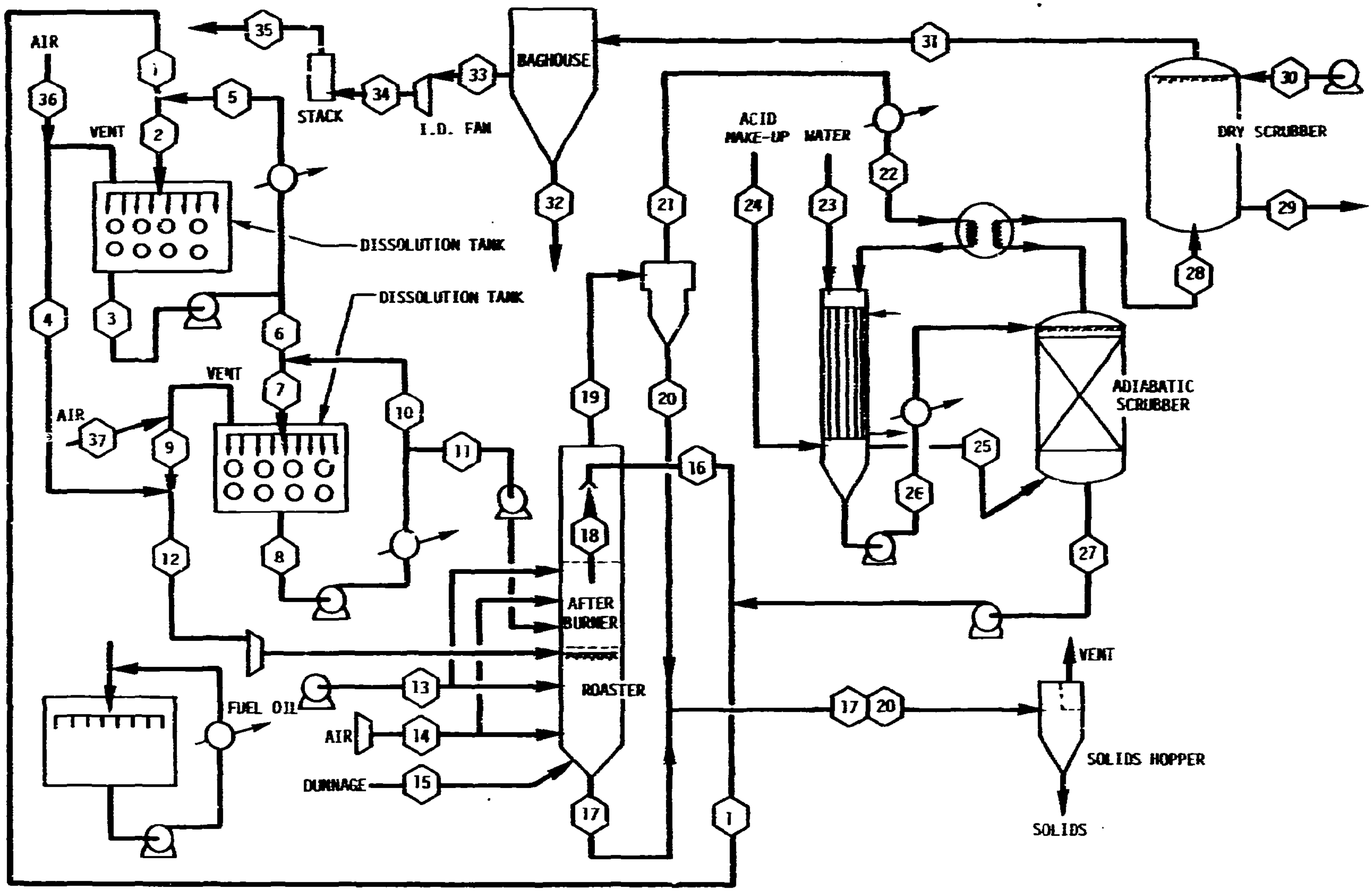



FIGURE D-3. ACID ROASTING

# TABLE D-1. ENERGY AND MATERIAL BALANCE - ACID ROASTER

| STREAM | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| TEMP DEG C | 80.00 | 80.00 | 80.00 | 80.00 | 80.00 | 80.00 | 80.00 | 80.00 | 80.00 | 80.00 |
| PRESSURE PSIA | 14.70 | 14.70 | 14.70 | 14.70 | 14.70 | 14.70 | 14.70 | 14.70 | 14.70 | 14.70 |
| ENTHALPY BTU | 2032953. | 12756095. | 12881167. | 2099220. | 10734307. | 2146861. | 13506537. | 13631609. | 2099220. | 11359674. |
| | | | | | | | | | | |
| HYDROCHLORIC AC | 4459.67 | 19701.87 | 18290.65 | 73.32 | 15242.21 | 3048.44 | 11234.54 | 9823.31 | 73.32 | 8186.09 |
| WATER | 10405.89 | 60827.55 | 60505.99 | 321.55 | 50421.66 | 10084.33 | 58898.22 | 58576.67 | 321.55 | 48813.89 |
| FERROUS CHLORID | 0.00 | 11627.73 | 13953.27 | 0.00 | 11627.73 | 2325.55 | 25581.00 | 27906.55 | 0.00 | 23255.46 |
| FERRIC CHLORIDE | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| HYDROGEN | 0.00 | 0.00 | 0.00 | 36.99 | 0.00 | 0.00 | 0.00 | 0.00 | 36.99 | 0.00 |
| NITROGEN | 0.00 | 0.00 | 0.00 | 9311.71 | 0.00 | 0.00 | 0.00 | 0.00 | 9311.71 | 0.00 |
| CARBON DIOXIDE | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| OXYGEN | 0.00 | 0.00 | 0.00 | 2018.36 | 0.00 | 0.00 | 0.00 | 0.00 | 2818.36 | 0.00 |
| FERRIC OXIDE | 17.58 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| PHOSPHORIC ACID | 69.96 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| HYDROFLUORIC AC | .29 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| AGENT | 0.00 | 1000.00 | 1200.00 | 0.00 | 1000.00 | 200.00 | 2200.00 | 2400.00 | 0.00 | 2000.00 |
| FUEL OIL | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| DUNNAGE | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| EXPLOSIVES | 0.00 | 625.00 | 750.00 | 0.00 | 625.00 | 125.00 | 1375.00 | 1500.00 | 0.00 | 1250.00 |
| SODIUM HYDROXID | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | | | | | | | | | |
| TOTAL LB/HR | 14953.37 | 93782.15 | 94699.92 | 12561.94 | 78916.59 | 15783.32 | 99288.76 | 100206.53 | 12561.94 | 83505.44 |
| TOTAL LB-MOL/HR | 700.75 | 4016.91 | 3980.41 | 458.69 | 3317.00 | 663.40 | 3797.87 | 3761.36 | 458.69 | 3134.47 |
| | | | | | | | | | | |
| HYDROGEN | 1289.68 | 7445.59 | 7389.70 | 74.99 | 6158.08 | 1231.62 | 7110.25 | 7054.36 | 74.99 | 5878.63 |
| CARBON | 0.00 | 539.02 | 646.83 | 0.00 | 539.02 | 107.80 | 1185.85 | 1293.66 | 0.00 | 1078.05 |
| OXYGEN | 9292.44 | 54597.71 | 54427.50 | 3103.94 | 45356.25 | 9071.25 | 53576.41 | 53406.20 | 3103.94 | 44505.16 |
| SULPHUR | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| NITROGEN | 0.00 | 57.19 | 68.62 | 9311.71 | 57.19 | 11.44 | 125.81 | 137.25 | 9311.71 | 114.37 |
| PHOSPHOROUS | 22.11 | 221.10 | 265.32 | 0.00 | 221.10 | 44.22 | 486.42 | 530.64 | 0.00 | 442.20 |
| FLUORINE | .27 | 135.60 | 162.72 | 0.00 | 135.60 | 27.12 | 298.32 | 325.44 | 0.00 | 271.20 |
| CHLORINE | 4336.58 | 25662.65 | 25591.29 | 71.30 | 21326.07 | 4265.21 | 25234.47 | 25163.11 | 71.30 | 20969.26 |
| IRON | 12.29 | 5123.18 | 6147.81 | 0.00 | 5123.18 | 1024.64 | 11270.99 | 12295.62 | 0.00 | 10246.35 |

## TABLE D-1, continued

| STREAM | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|
| TEMP DEG C | 80.00 | 80.00 | 20.00 | 20.00 | 20.00 | 80.00 | 800.00 | 750.00 | 320.00 | 320.00 |
| PRESSURE PSIA | 14.70 | 14.70 | 14.70 | 14.70 | 14.70 | 14.70 | 14.70 | 14.70 | 14.70 | 14.70 |
| ENTHALPY BTU | 2271935. | 4198439. | 142312. | 1052467. | 68599. | 9817241. | 1164129. | 43706100. | 53537988. | 36498. |
| | | | | | | | | | | |
| HYDROCHLORIC AC | 1637.22 | 146.65 | 0.00 | 0.00 | 0.00 | 21654.90 | 0.00 | 4459.62 | 26114.52 | 0.00 |
| WATER | 9762.73 | 643.11 | 0.00 | 0.00 | 0.00 | 50528.10 | 0.00 | 12463.85 | 62991.96 | 0.00 |
| FERROUS CHLORID | 4631.09 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| FERRIC CHLORIDE | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| HYDROGEN | 0.00 | 73.98 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| NITROGEN | 0.00 | 18623.42 | 0.00 | 6118.31 | 0.00 | 0.00 | 0.00 | 24764.68 | 24764.68 | 0.00 |
| CARBON DIOXIDE | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 6057.34 | 6057.34 | 0.00 |
| OXYGEN | 0.00 | 5636.73 | 0.00 | 1816.27 | 0.00 | 0.00 | 0.00 | 677.55 | 677.55 | 0.00 |
| FERRIC OXIDE | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 2754.06 | 175.79 | 175.79 | 158.21 |
| PHOSPHORIC ACID | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 139.91 | 139.91 | 139.91 | 0.00 |
| HYDROFLUORIC AC | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 54.27 | 2.86 | 2.86 | 2.57 |
| AGENT | 400.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| FUEL OIL | 0.00 | 0.00 | 1348.45 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| DUNNAGE | 0.00 | 0.00 | 0.00 | 0.00 | 650.00 | 0.00 | 65.00 | 0.00 | 0.00 | 0.00 |
| EXPLOSIVES | 250.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| SODIUM HYDROXID | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | | | | | | | | | |
| TOTAL LB/HR | 16701.09 | 25123.88 | 1348.45 | 7934.58 | 650.00 | 72183.00 | 3013.24 | 48741.61 | 120924.62 | 160.78 |
| TOTAL LB-MOL/HR | 626.89 | 917.37 | .00 | 275.17 | 4.01 | 3398.56 | 21.79 | 1859.66 | 5258.22 | 1.12 |
| | | | | | | | | | | |
| HYDROGEN | 1175.73 | 149.99 | 167.21 | 0.00 | 36.40 | 6251.77 | 10.70 | 1522.26 | 7774.03 | .13 |
| CARBON | 215.61 | 0.00 | 1175.85 | 0.00 | 260.13 | 0.00 | 26.01 | 1653.05 | 1653.05 | 0.00 |
| OXYGEN | 8901.03 | 6207.87 | .54 | 1816.27 | 288.73 | 44874.00 | 948.12 | 16295.21 | 61169.21 | 47.56 |
| SULPHUR | 0.00 | 0.00 | 2.29 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| NITROGEN | 22.87 | 18623.42 | .08 | 6118.31 | 0.00 | 0.00 | 0.00 | 24764.68 | 24764.68 | 0.00 |
| PHOSPHOROUS | 88.44 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 44.23 | 44.23 | 44.23 | 0.00 |
| FLUORINE | 54.24 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 51.54 | 2.71 | 2.71 | 2.44 |
| CHLORINE | 4193.85 | 142.60 | 0.00 | 0.00 | 0.00 | 21057.22 | 0.00 | 4336.54 | 25393.76 | 0.00 |
| IRON | 2049.27 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1926.19 | 122.95 | 122.95 | 110.65 |

TABLE D-1, continued

| STREAM | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 |
|---|---|---|---|---|---|---|---|---|---|---|
| TEMP DEG C | 320.00 | 113.00 | 20.00 | 20.00 | 80.00 | 80.00 | 80.00 | 75.00 | 75.00 | 40.00 |
| PRESSURE PSIA | 14.70 | 14.70 | 14.70 | 14.70 | 14.70 | 14.70 | 14.70 | 14.70 | 14.70 | 14.70 |
| ENTHALPY BTU | 53501496. | 13919142. | 22759. | 17017. | 16319267. | 4298666. | 11850194. | 5916484. | 26692. | 91125. |
| | | | | | | | | | | |
| HYDROCHLORIC AC | 26114.52 | 26114.52 | 0.00 | 70.19 | 20947.77 | 5236.94 | 26114.57 | 70.14 | 68.04 | 0.00 |
| WATER | 62991.96 | 62991.96 | 632.20 | 280.75 | 30336.31 | 25568.60 | 60933.99 | 2970.92 | 0.00 | 1078.07 |
| FERROUS CHLORID | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| FERRIC CHLORIDE | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| HYDROGEN | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| NITROGEN | 24764.68 | 24764.68 | 0.00 | 0.00 | 24764.68 | 0.00 | 0.00 | 24764.68 | 0.00 | 0.00 |
| CARBON DIOXIDE | 6057.34 | 6057.34 | 0.00 | 0.00 | 6057.34 | 0.00 | 0.00 | 6057.34 | 0.00 | 0.00 |
| OXYGEN | 677.55 | 677.55 | 0.00 | 0.00 | 677.55 | 0.00 | 0.00 | 677.55 | 0.00 | 0.00 |
| FERRIC OXIDE | 17.58 | 17.58 | 0.00 | 0.00 | 0.00 | 17.58 | 17.58 | 0.00 | 0.00 | 0.00 |
| PHOSPHORIC ACID | 139.91 | 139.91 | 0.00 | 0.00 | 139.91 | 0.00 | 69.96 | 69.96 | 33.93 | 0.00 |
| HYDROFLUORIC AC | .29 | .29 | 0.00 | 0.00 | .29 | 0.00 | .29 | 0.00 | 0.00 | 0.00 |
| AGENT | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| FUEL OIL | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| DUNNAGE | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| EXPLOSIVES | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| SODIUM HYDROXID | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 116.19 | 119.79 |
| | | | | | | | | | | |
| TOTAL LB/HR | 120763.84 | 120763.84 | 632.20 | 350.94 | 90923.86 | 30823.12 | 87136.37 | 34610.59 | 218.16 | 1197.85 |
| TOTAL LB-MOL/HR | 5257.10 | 5257.10 | 35.09 | 17.51 | 3746.74 | 1562.96 | 4099.31 | 1210.39 | 5.12 | 62.83 |
| | | | | | | | | | | |
| HYDROGEN | 7773.90 | 7773.90 | 70.74 | 33.35 | 4872.33 | 3005.67 | 7541.45 | 336.54 | 5.85 | 123.65 |
| CARBON | 1653.05 | 1653.05 | 0.00 | 0.00 | 1653.05 | 0.00 | 0.00 | 1653.05 | 0.00 | 0.00 |
| OXYGEN | 61121.66 | 61121.66 | 561.46 | 249.34 | 39219.69 | 22712.76 | 54166.45 | 7766.00 | 68.64 | 1005.35 |
| SULPHUR | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| NITROGEN | 24764.68 | 24764.68 | 0.00 | 0.00 | 24764.68 | 0.00 | 0.00 | 24764.68 | 0.00 | 0.00 |
| PHOSPHOROUS | 44.23 | 44.23 | 0.00 | 0.00 | 44.23 | 0.00 | 22.11 | 22.11 | 10.72 | 0.00 |
| FLUORINE | .27 | .27 | 0.00 | 0.00 | .27 | 0.00 | .27 | 0.00 | 0.00 | 0.00 |
| CHLORINE | 25393.76 | 25393.76 | 0.00 | 68.25 | 20369.61 | 5092.40 | 25393.80 | 68.21 | 66.16 | 0.00 |
| IRON | 12.29 | 12.29 | 0.00 | 0.00 | 0.00 | 12.29 | 12.29 | 0.00 | 0.00 | 0.00 |

TABLE D-1, continued

| STREAM | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 |
|---|---|---|---|---|---|---|---|---|---|---|
| TEMP DEG C | 70.00 | 70.00 | 70.00 | 70.00 | 7 00 | 70.00 | 70.00 | 70.00 | 70.00 | 70.00 |
| PRESSURE PSIA | 14.70 | 14.70 | 14.70 | 14.70 | 14.70 | 14.70 | 14.70 | 14.70 | 14.70 | 14.70 |
| ENTHALPY BTU | 6101767. | 814. | 6100954. | 6100954. | 6100954. | 1874322. | 1874322. | 0. | 0. | 0. |
| HYDROCHLORIC AC | 2.10 | 2.10 | .00 | .0[illegible] | .0[illegible] | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| WATER | 4048.99 | 0.00 | 4048.99 | 4048.99 | 4048.99 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| FERROUS CHLORID | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| FERRIC CHLORIDE | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| HYDROGEN | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| NITROGEN | 24764.68 | 0.00 | 24764.68 | 24764.68 | 24764.68 | 9311.71 | 9311.71 | 0.00 | 0.00 | 0.00 |
| CARBON DIOXIDE | 6057.34 | 0.00 | 6057.34 | 6057.34 | 6057.34 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| OXYGEN | 677.55 | 0.00 | 677.55 | 677.55 | 677.55 | 2818.36 | 2818.36 | 0.00 | 0.00 | 0.00 |
| FERRIC OXIDE | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| PHOSPHORIC ACID | 36.03 | 1.05 | 34.98 | 34.98 | 34.98 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| HYDROFLUORIC AC | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| AGENT | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| FUEL OIL | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| DUNNAGE | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| EXPLOSIVES | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| SODIUM HYDROXID | 3.59 | 3.59 | .00 | .0[illegible] | .0[illegible] | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| TOTAL LB/HR | 35590.29 | 6.75 | 35583.54 | 35583.54 | 35583.54 | 12130.07 | 12130.07 | 0.00 | 0.00 | 0.00 |
| TOTAL LB-MOL/HR | 1268.11 | .16 | 1267.95 | 1267.95 | 1267.95 | 420.48 | 420.48 | 0.00 | 0.00 | 0.00 |
| HYDROGEN | 454.34 | .18 | 454.16 | 454.16 | 454.16 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CARBON | 1653.05 | 0.00 | 1653.05 | 1653.05 | 1653.05 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| OXYGEN | 8702.71 | 2.12 | 8700.59 | 8700.59 | 8700.59 | 2818.36 | 2818.36 | 0.00 | 0.00 | 0.00 |
| SULPHUR | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| NITROGEN | 24764.68 | 0.00 | 24764.68 | 24764.68 | 24764.68 | 9311.71 | 9311.71 | 0.00 | 0.00 | 0.00 |
| PHOSPHOROUS | 11.39 | .33 | 11.06 | 11.06 | 11.06 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| FLUORINE | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CHLORINE | 2.05 | 2.05 | .00 | .0[illegible] | .0[illegible] | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| IRON | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

## D. Ultimate Disposal

The oxides and ash from the roaster should satisfy RCRA landfill criteria and could have a significant resale value. As designed, the quantities of NaCl produced by the pollution abatement system will be larger than the baseline. While in the baseline, such salts must be disposed of in a hazardous materials landfill, this potential problem is diminished in this concept by the following considerations:

- The quantities projected in the material balance represent a worst-case that could be markedly reduced by refinement of the concept
- The salts are not produced from or by agent and as such may be more readily certified agent free.

## E. Concept Advantages

The key advantage of this concept is its ability to process feedstock configuration b eliminating the costly disassembly operations from the baseline. In addition, the process concept subjects all items and agents to the same processing steps. This produces a simple system without branching and, coupled with elimination of disassembly, removes the costly change over periods from the processing schedule. The final advantage is that commercially proven hardware is utilized. The agent destruction furnace design is based on liquid injection incineration which is state-of-the-art technology for disposal of hazardous liquids. The acid regeneration system is also adapated from state-of-the-art technology. Besides Dravo Engineers, Lurgi and Woodall-Duckham Ltd design and license acid recovery systems. Dravo Engineers have expressed a willingness to support the development effort for this concept.

## F. Concept Disadvantages

The major disadvantages of this concept is the expensive materials of construction and lack of economy of scale do to the need for multiple units at high throughput. The combination of these two facts lead to escalation of the capital equipment costs for a collocated facility. The final disadvantage is the possible increased salt disposal problem discussed previously.

## G. System Concept Knowledge Gaps

As related to agent destruction, the key knowledge gap is whether the agents and their decomposition products can be destroyed effectively under conditions conducive to roasting iron chlorides. Incompatibilities in these reactions which occur simultaneously could lead to reduced acid recovery and an increased pollution abatement demand. However, since the temperature and residence time requirements for both reactions are similar this is not anticipated to be a problem. In fact, it is anticipated that the presence of iron salts in the incinerator might even enhance agent destruction efficiencies.

The knowledge gaps most critical to successful implementation of the concept is the behavior of the explosives. There is evidence that acid solutions will decompose explosives[4,5]. While documents suggest that the combination of hot nitric acid and iron salts in an oxidizing system has the potential to sensitize explosives to friction and impact, no such evidence exists for the hydrochloric acid/hydrogen system proposed here.

Based on the literature data, a conservative estimate was made of the rate at which acid will dissolve the metal parts. Confirmation of the dissolution rate with the actual acid stream composition is required. Rates slower than those predicted would require additional dissolution tanks and, while increasing the costs, would not significantly effect the viability of the concept. However,

if it can be shown that, as suspected, markedly faster rates can be achieved, then operating at lower acid concentrations and/or temperatures would be practice. These parameters can have major impact on the waste stream disposal and possibly the safety scenarios.

The final knowledge gap is one that all concepts have in common, materials compatibility problems. While commercial hydrochloric acid roasting units exist that have been in service for 20 years, none of these units contain acids of sulfur, phosphorous, and fluorine along with the hydrochloric acid. The fate and impact of these materials contributed by the agent destruction process must be determined.

## H. Safety

Standard acid plant safety guidelines must be followed in the design and operation of this concept. This includes curbing the dissolution tank room to contain spills and the avoidance where possible of overhead acid lines. Hazards associated with the hydrogen vent stream have also been addressed in the design. In addition, the dissolution area is manned only during tank loading and operating personnel would not be exposed to detonation hazards should experimental work should prove that sensitization of explosives occurs during acid dissolution.

## I. Likelihood of Development Within Five Years

The majority of the process steps use state-of-the-art technology. While several knowledge gaps have been identified, none appear to be a barrier to development of the concept. Even determination that the explosives are sensitized by the acid could be resolved technically. Introduction of a step for desensitizing the explosives could be included. Resolution of this issue could also be accomplished at the expense of process economics (e.g., reducing the size of the vats, imposition of quantity/distance requirements, and/or strengthening the tanks to contain a detonation).

## J. Scalability to 400-3000 Pounds/Hour of Agent

At the agent rate of 400 lb/hr of agent, the roasting and acid reclamation systems are operating at near capacity. Consequently, scaling to higher rates soon requires installation of parallel systems. Therefore, while scaling to higher throughputs is technically feasible, no economy of scale is anticipated.

## K. Degree of Technical Risk

As previously discussed, the major system components are commercially available. No technology gaps exist and the knowledge gaps that have been identified deal mostly with possible improvements of the concept design.

## L. RAM Factors

A detailed analysis of the availability and maintainability of this concept can be found in Appendix L. It should be pointed out that built-in redundancy has been incorporated in the design and cost estimation for those equipment items that are considered most likely to have failures. However, following Army guidelines, the RAM analysis permits no credit for this redundancy. In fact, due to the increase in equipment items, strict adherence to the RAM analysis guidelines yields a system availability that is lower than would be determined if the redundancy was not present.

## M. Materials Compatibility Problems

The state-of-the-art hardware is designed to be acid resistant. With the exception of attack of the roaster refractory by HF, no additional materials compatibility problems are anticipated.

## N. Energy Requirements and Source

The roasting process requires the high use of fuel oil to evaporate the acid and water. It is anticipated that a significant concept refinement effort would be focused on reducing the fuel demand by minimizing the quantity of acid being roasted. This could lead to a marked reduction in the operating costs for this concept.

## O. Ease of Operation

As designed, this is one of the simplest concepts to operate. A minimum of moving parts exists and all agents and items/munitions in the inventory are processed in the same manner, simply load the tanks and start the acid. There are no complex variables to control and no complex hardware to operate.

## Economic Analysis

The design specifications received from Dravo Engineers Incorporated[12] included a cost estimate of $7M (1981) for a turnkey operation. But, this estimate included hardware such as a tank farm that this concept does not require. It also included items beyond the scope of the thermal process (e.g., site improvements, utilities). Since Dravo considers the individual cost items proprietary, it was not possible to use their cost estimate directly. However, the equipment size specification supplied by Dravo was quite useful in producing the following estimation of the costs.

## A. Facility Costs

Army guidelines were used for the costs of constructing the various buildings required by this concept. It was assumed that all operations downstream of the roaster were non-agent and the commercial practice of installation on pads could be utilized. The dissolution

tanks and the roaster were assumed to be agent containment facilities and were costed accordingly. While the tanks are not designed for blast containment, the facility costs for agent containment and blast containment are the same.

To determine the areas in each building category required for these types of facilities, plot plans were constructed for 400 lb/hr and 5000 lb/hr of agent based on the sizes of the identified equipment items. The areas determined from these plans were used to determine exponential scaling factors for each building category. These factors were then used to determine the building and pad areas for the other plant sizes. The estimated facility costs calculated in this manner are summarized in Tables D-2 (Single Site) and D-3 (Collocated).

## B. Capital Equipment Costs

Costing Method. Detailed capital equipment cost estimates were generated on an item-by-item basis for a plant size capable of handling 400 lb/hr of agent. The equipment size specifications for the pickling liquor plant supplied by Dravo Engineering Inc were used to estimate the acid regeneration system equipment sizes. Each equipment item cost was then derived from standard relationships between the appropriate size parameter and cost which are documented in Guthrie[16], Peters and Timmerhaus[17] and others. Factors were used to convert the costs derived for carbon steel equipment computed from these relationships to corrected values for items constructed of corrosion resistant materials such as graphite, fiberglass-reinforced plastic (FRP), and palladium-stabilized titanium. These factors vary according to equipment item and they correct for both the cost of materials and the difficulty of fabrication. The Marshal and Swift installed equipment index was used to correct all costs for the 400 lb/hr facility to mid-1982 dollars.

Equipment costs for the other size plants were then computed based on exponential sizing factors derived from Guthrie or Peters and

TABLE D-2. ACID ROASTING FACILITY COSTS - SINGLE SITE

| Item | Agent Destruction Rate | | |
|---|---|---|---|
| | 100 lb/hr | 400 lb/hr | 1000 lb/hr |
| Dissolution Area - | | | |
| Surety (1 floor) | 1320 $ft^2$ | 1520 $ft^2$ | 3400 $ft^2$ |
| at $400/$ft^2$ | $528,000 | $608,000 | $1,360,000 |
| Furnace Area - | | | |
| Surety (50' high) | 144 $ft^2$ | 361 $ft^2$ | 950 $ft^2$ |
| at $400/$ft^2$ | $57,600 | $144,400 | $380,000 |
| Outside Pads - | | | |
| Acid Recovery | 200 $ft^2$ | 600 $ft^2$ | 1600 $ft^2$ |
| Pollution Abatement | 180 $ft^2$ | 550 $ft^2$ | 1500 $ft^2$ |
| Ore Handling & Storage | 1500 $ft^2$ | 5000 $ft^2$ | 12,000 $ft^2$ |
| Salt Handling | 1000 $ft^2$ | 2500 $ft^2$ | 4300 $ft^2$ |
| Fuel Tank | 1320 $ft^2$ | 3460 $ft^2$ | 6000 $ft^2$ |
| Total Pad Costs at $2.50/$ft^2$ | $10,500 | $30,275 | $63,500 |
| Total Facility | $596,100 | $782,675 | $1,803,500 |

TABLE D-3. ACID ROASTING FACILITY COSTS - COLLOCATED SITE

| Item | Agent Destruction Rate | | |
|---|---|---|---|
| | 1000 lb/hr | 3000 lb/hr | 5000 lb/hr |
| Dissolution Area - | 3400 $ft^2$ | 9100 $ft^2$ | 14,384 $ft^2$ |
| at $400/$ft^2$ | $1,360,000 | $3,640,000 | $5,753,600 |
| Furnace Area - | 950 $ft^2$ | 3050 $ft^2$ | 5208 $ft^2$ |
| at $400/$ft^2$ | $380,000 | $1,220,000 | $2,083,200 |
| Outside Pads - | | | |
| Acid Recovery | 1600 $ft^2$ | 5500 $ft^2$ | 9500 $ft^2$ |
| Pollution Abatement | 2500 $ft^2$ | 8500 $ft^2$ | 15,000 $ft^2$ |
| Ore Handling & Storage | 15,000 $ft^2$ | 40,000 $ft^2$ | 60,000 $ft^2$ |
| Salt Handling | 6000 $ft^2$ | 15,000 $ft^2$ | 20,000 $ft^2$ |
| Fuel Tank | 6000 $ft^2$ | 12,000 $ft^2$ | 16,000 $ft^2$ |
| Total Pad Area | 31,100 $ft^2$ | 81,000 $ft^2$ | 120,500 $ft^2$ |
| Total Pad Costs at $2.50/$ft^2$ | $77,750 | $202,500 | $301,250 |
| Total Facility | $1,817,750 | $5,062,500 | $8,138,050 |

Timmerhaus that could be applied to the 400 lb/hr agent case. The factors used were a characteristic of each type of chemical process equipment. In many cases the maximum or minimum equipment size limits were imposed by practical considerations. In these instances, the costing was based on the use of a minimum number of equal size items that could perform the function operating in parallel.

For each facility size the total plant equipment purchase costs were then summarized and additional capital equipment costs were calculated by applying the multiplication factors for installation, instrumentation, piping, electrical and design that are recommended on page 180 of Peters and Timmerhaus. Additional rationale behind the computation of the individual equipment items is discussed below.

<u>Equipment Item Costs</u>.

Vessels. The dissolution tanks, roaster cyclone, solids hopper, stack, and dry scrubber were considered to be pressure vessels. Vessel costs were based on the weight of steel using the following equations from Mulet[18].

Vessel Cost

$$= \text{Exp}\,(8.8 - 0.28885\ \text{lm (weight)} + 0.04576\ \ln\ (\text{weight})^2)$$

Platform and Accessory Cost

$$= 182.5\ (\text{diam. ft})^{0.7396}\ (\text{Height ft.})^{0.70684}$$

These costs are for the first quarter of 1979.

Insulation costs for the roaster cyclone are from Koenig[19] and are based on external surface area.

The dissolution tanks lining of either hard rubber or plastic was costed at $12.00/ft$^2$[16] The calculated cost of the dissolution tanks might be low because no correction was used to account for the complexity of a sealable, vertical 6' x 6' door.

The dry scrubber is constructed of FRP and a multiplier of 1.1 was used to correct for this material.

Fans and Blowers. The costs of the fans and blowers was derived from page 562 of Peters and Timmerhaus, and were based on capacity in cfm. The dissolution vent fans, furnace air fan, and induced draft (I.D.) fan were all sized as centrifugal blowers and the oxide blower sized as a rotary blower. The predicted costs of the furnace air fan and I.D. fan are probably high due to their lower pressure ratio. This factor is compensated in the dissolution vent fans by the need for a corrosion resistant lining. Otherwise, the fans and blowers are of standard construction. Motors are totally enclosed, fan-cooled.

Pumps. All pumps were costed as centrifugal, horizontal, in-line pumps. The costs used were derived as suggested on page 557 of Peters and Timmerhaus, and were based on capacity in gpm multiplied by head in psi. The following equations from Corripio[20] were used as an addition check and for sizing:

s = (gpm) Heat ft.

Base cost = Exp (8.3949 - 0.6019 ln(s) + 0.0519 ln(s)$^2$)

Correction Factor (1750 rpm, horizontal)
= Exp (2.029 -0.2371 ln(s) + 0.0102 ln(s))

Correction Factor (3550 rpm,horizontal)
= Exp (0.0632 + 0.2744 ln(s) - 0.0253 ln(s)$^2$)

Pump Efficiency = 0.316 + 0.24015 ln (gpm) - 0.01199 ln (gpm)$^2$
(19 to 5000 gpm)

Motor Efficiency = 0.8 + 0.0319 ln (HP) - 0.00182 ln (HP)$^2$
(1 to 500 horsepower)

All pumps were considered to be palladium-stabilized titanium except the fuel oil pumps and the dry scrubber pumps. The multiplier for titanium construction of pumps is reported to be 9.7 by

Corripio[20] and 5.71 by Hall[21]. The lower number was used because Hall specifically claims to be current while Corripio does not. The reason for the discrepancy may either be due to improved titanium fabrication techniques or to more widespread use of titanium pumps. The potential error in plant cost due to this difference in factors is about 4 percent.

Pump motors are totally enclosed, fan cooled. Provisions must be made to double seal and return seal flush liquid to the process in all pumps except the fuel oil pumps.

Heat Exchangers. Costing on heat exchangers was based on the required heat transfer surface area and on materials of construction. The dissolution coolers, isothermal absorber and adiabatic scrubber cooler are all of graphite construction, while the cyclone gas cooler and dry scrubber preheater are palladium-stabilized titanium. American Vicarb[22] quoted a price of $\$70/ft^2 \pm 15\%$ for small graphite heat exchangers and $\$75/ft^2 \pm 15\%$ at sizes larger than 2000 $ft^2$. This company produces heat exchangers that can operate with hydrochloric acid at temperatures up to 200°C and claims to have worked with Dravo.

The following equations from Corripio[23] were used to calculate first quarter 1979 costs for the titanium heat exchangers:

$A$ = surface area in $ft^2$.

$$\text{Base Cost} = \text{Exp}\ (8.551 - 0.30863 \ln A + 0.06811 (\ln A)^2)$$

$$\text{Fixed Head Correction Factor} = \text{Exp}\ (-1.1156 + 0.0906 \ln A)$$

The costs for the two titanium heat exchangers calculated in this manner were 2.4 percent higher than those calculated using Peters and Timmerhaus.

Roaster-Afterburner. The cost for the roaster-afterburner was derived from charts presented by Hall[21] and were based on heat

utilization. The calculated cost assumes internal insulation and internal heat exchange tubes. The extra cost of the unnecessary heat exchange tubes were assumed to account for the cost of the afterburner, the titanium spray nozzles, and a slightly more expensive acid brick lining.

Adiabatic Scrubber. The cost of the adiabatic scrubber was obtained from charts to determine the vessel cost, connection, ladders, platforms, and packing costs given on pages 768-771 in Peters and Timmerhaus. Polypropylene, 1-inch intalox saddles were assumed to be the packing material. A multiplying factor of 1.1 was then used to convert carbon steel material cost to FRP material cost. The scrubber cost could be low, if the large diameter column that is specified requires the use of flow redistributions or high efficiency packing material.

Baghouse. The baghouse cost was calculated from the equation given by Vatavuk[24]:

$$\text{Cost} = 5370 + 7.6\ (\text{Bag Area in ft}^2).$$

This cost is based on carbon steel construction and continuous operation at negative pressure. Polypropylene bags were used at $0.70/ft^2$.

Cooling Tower. The cost of the cooling tower was based on the required cooling water flow rate using Figure 13 in Guthrie. The 1968 cost was scaled to mid-1982 using the respective Marshall and Swift indices of 273.1 and 746.

Scale-up Methods.

Vessels. The dissolution tanks, roaster cyclone, solids hopper, stack, and dry scrubber costs were derived from the 400 lb/hr

agent equipment costs using the vessel weight ratios to the 0.7 power. The exponent is from Desai[25]. Except for the dissolution tanks, the maximum single unit size was limited to a 13-ft diameter. As mentioned previously, the 6'x6'x16' size of the 400 lb-agent/hr dissolution tanks was taken to be the minimum size practical for material handling and the 6'x6'x16' size of the 1000 lb-agent/hr dissolution tanks was assumed to be the maximum allowable size. Two minimum size tanks were used in the 100 lb-agent/hr plant costing. The above constraints resulted in the number of units required for each plant size shown in Table D-4 below.

TABLE D-4. NUMBER OF VESSELS FOR EACH PLANT SIZE

| Plant Size (lb/hr Agent) | 100 | 400 | 1000 | 3000 | 5000 |
|---|---|---|---|---|---|
| Dissolution Tanks | 2 | 3 | 3 | 6 | 15 |
| Roaster Cyclones | 1 | 1 | 2 | 4 | 6 |
| Solids Hoppers | 1 | 1 | 3 | 7 | 12 |
| Stack | 1 | 1 | 1 | 1 | 1 |
| Dry Scrubbers | 1 | 1 | 1 | 3 | 4 |

Fans and Blowers. In all cases the fans and blowers were scaleable to each plant size using single units. The exponents used for relating relative costs to size was 0.65 for the fans and 0.75 for the oxides blower. These exponents were also given by Desai. The size parameter was capacity in standard cubic feet per minute.

Pumps. There were no size limitations on the pumps and in each plant size. The basis for scaling costs from the 400 lb/hr size to the other sizes was the ratio of pump capacities in gpm raised to the 0.6 power. This exponent is from Desai. Pump sparing was 100

percent for all pumps except the dissolution pumps in the 1000, 3000, and 5000 lb-agent/yr plant sizes. In these cases, each bank of dissolution tanks ,out of a total of three, is serviced by 3 half-size pumps to yield 9 total pumps per plant.

Heat Exchangers. Single unit heat exchanger sizes were limited to 20-foot tube lengths and 37-inch tube sheet diameter. The size constraints limited the size of the cyclone gas cooler in all cases except 100 lb/hr and limited the isothermal absorber only in the 5000 lb/hr plant size. Because definite costs were given for each square foot of graphite heat exchange surface, the size limitations only affected the cost of the titanium cyclone gas cooler. The exponent for scaling the titanium heat exchanger costs from the heat transfer, surface area was 0.6 from Desai.

Roaster-Afterburner. The roaster-afterburner was limited to a single unit size capable of processing 1000 lb/hr of agent. This occurs at a diameter of 20 feet. Larger diameters are likely to result in non-uniform reaction conditions in the vortexing flame. The cost sizing exponent used was 0.87 from Corripio.

Adiabatic Scrubber. The single unit absorber size was limited to 13 feet which corresponds to a maximum plant size of 1730 lb-agent/hr. The cost scaling was based on vessel weight ratios raised to the 0.7 power. this exponent was given by Desai. Although packing cost is proportional to the absorber volume, the absorber volume is in turn roughly proportional to the vessel weight raised to the 1.08 power. Thus, vessel weight is a good size parameter and was used to scale the cost scaling.

Baghouse. Baghouse costs are directly proportional to size. Consequently, there are no size limitations to scaling.

Cooling Tower. There were no size limitations to the cooling tower in the plant size ranges of interest. Costs were scaled by the water flowrate ratio raised to the 0.6 power. The exponent was given in Guthrie.

The total capital equipment costs estimated in this means for single site are summarized in Table D-5. The collocation capital equipment costs are summarized in Table D-6.

## C. Operating Costs

To estimate the total life cycle operating costs, it was first necessary to determine the labor requirements as well as the other operating costs on a yearly basis. The inventory quantity, the item processing rate, and the system availability were then used to determine the years of production required for each category. Those numbers were then multipled by the operating costs to produce the life cycle operating costs.

Labor Costs. The system personnel requirements summarized in Table D-7 were estimated from the information supplied by Dravo.

Other Direct Costs. At the 400 lb/hr of agent throughput, the quantities of water, fuel oil, HCL makeup, and caustic used as well as the quantities of $Fe_2O_3$ and NaCl produced were gleaned from the material balance. The electricity requirements for this capacity were estimated from the size and quantity of electric motors. To determine the requirements for these items at other agent throughput rates, it was assumed that demand would scale linearly with throughput, a reasonable assumption for this process.

The Army guidelines were used for the charge rates for water, electricity, and fuel oil. Caustic and acid costs were determined from present market costs. Disposal costs for $Fe_2O_3$ were assumed to be only the trucking costs which were estimated at $5/ton. As a worst case assumption, the NaCl salts were assumed to require

TABLE D-5. CAPITAL EQUIPMENT INSTALLED COSTS - SINGLE SITE

| Item | Agent Destruction Rate | | |
|---|---|---|---|
| | 100 lb/hr | 400 lb/hr | 1000 lb/hr |
| Dissolution Area | | | |
| Dissolution Tanks | $ 56,000 | $ 84,000 | $ 196,000 |
| Dissolution Vent Fants | 4,549 | 11,200 | 20,318 |
| Dissolution Pumps | 9,140 | 21,000 | 36,009 |
| Dissolution Coolers | 4,832 | 11,100 | 19,235 |
| SUBTOTAL | $ 74,521 | $ 127,300 | $ 271,562 |
| Furnace Area | | | |
| Roaster-Afterburner | $ 207,463 | $ 693,000 | $ 1,999,230 |
| Roaster Feed Pumps | 4,135 | 9,500 | 16,462 |
| Fuel Oil Pumps | 1,567 | 3,600 | 6,238 |
| Furnace Air Fan | 6,072 | 14,950 | 27,121 |
| Roaster Cyclone | 7,920 | 20,900 | 48,867 |
| Oxide Blower | 1,326 | 3,750 | 7,456 |
| SUBTOTAL | $ 228,483 | $ 745,700 | $ 2,105,474 |
| Acid Regeneration Area | | | |
| Cyclone-Gas Cooler | $ 168,369 | $ 510,400 | $ 1,276,000 |
| Adiabatic Scrubber | 24,706 | 65,200 | 123,824 |
| Absorber Feed Pump | 14,843 | 34,100 | 59,090 |
| Absorber Bottom Pump | 17,672 | 40,600 | 70,354 |
| Adiabatic Scrubber Cooler | 1,328 | 3,050 | 5,285 |
| Isothermal Absorber | 8,880 | 20,400 | 35,350 |
| Cooling Tower | 53,495 | 122,900 | 212,969 |
| SUBTOTAL | $ 289,293 | $ 796,650 | $ 1,782,872 |
| Pollution Abatement Area | | | |
| Dry Scrubber | $ 8,336 | $ 22,000 | $ 41,781 |
| Dry Scrubber Preheater | 29,794 | 68,450 | 118,614 |
| Dry Scrubber Pumps | 1,698 | 3,900 | 6,758 |
| Baghouse | 11,212 | 44,850 | 112,125 |
| Stack | 6,669 | 17,600 | 33,425 |
| I.D. Fan | 9,605 | 23,650 | 42,903 |
| Solids Hopper | 14,728 | 39,000 | 102,909 |
| Fuel Tanks | 36,000 | 90,000 | 155,957 |
| SUBTOTAL | $ 118,082 | $ 309,540 | $ 614,472 |
| Total Equipment Purchase Costs | $ 710,379 | $ 1,979,100 | $ 4,774,380 |
| Installation (40%) | 284,152 | 791,640 | 1,909,752 |
| Instrumentation (13%) | 92,349 | 257,283 | 620,669 |
| Piping (31%) | 220,217 | 613,521 | 1,480,058 |
| Electrical (10%) | 71,038 | 197,910 | 477,438 |
| SUBTOTAL | $1,378,135 | $ 3,839,454 | $ 9,262,297 |
| DESIGN (32%) | 441,003 | 1,228,625 | 2,963,935 |
| Total Capital Equipment | $1,819,138 | $ 5,068,079 | $12,226,232 |

TABLE D-6. CAPITAL EQUIPMENT INSTALLED COSTS - COLLOCATED SITE

| Item | Agent Destruction Rate 1000 lb/hr | 3000 lb/hr | 5000 lb/hr |
|---|---|---|---|
| Dissolution Area | | | |
| Dissolution Tanks | $ 196,000 | $ 590,859 | $ 984,765 |
| Dissolution Vent Fants | 20,318 | 41,496 | 57,838 |
| Dissolution Pumps | 36,009 | 69,619 | 94,588 |
| Dissolution Coolers | 19,235 | 37,184 | 50,520 |
| SUBTOTAL | $ 271,562 | $ 739,158 | $ 1,187,711 |
| Furnace Area | | | |
| Roaster-Afterburner | $ 1,999,330 | $ 5,997,989 | $ 9,996,648 |
| Roaster Feed Pumps | 16,462 | 31,824 | 43,238 |
| Fuel Oil Pumps | 6,238 | 12,060 | 16,385 |
| Furnace Air Fan | 27,121 | 55,390 | 77,203 |
| Roaster Cyclone | 48,867 | 129,810 | 209,618 |
| Oxide Blower | 7,456 | 16,995 | 24,930 |
| SUBTOTAL | $ 2,105,474 | $ 6,244,068 | $10,368,022 |
| Acid Regeneration Area | | | |
| Cyclone-Gas Cooler | $ 1,276,000 | $ 3,615,037 | $ 5,950,211 |
| Adiabatic Scrubber | 123,824 | 328,927 | 531,155 |
| Absorber Feed Pump | 59,090 | 114,233 | 155,203 |
| Absorber Bottom Pump | 70,354 | 136,007 | 184,787 |
| Adiabatic Scrubber Cooler | 5,285 | 10,217 | 13,882 |
| Isothermal Absorber | 35,350 | 68,339 | 122,515 |
| Cooling Tower | 212,969 | 411,707 | 559,368 |
| SUBTOTAL | $ 1,782,872 | $ 4,684,467 | $ 7,517,121 |
| Pollution Abatement Area | | | |
| Dry Scrubber | 41,781 | 125,343 | 195,379 |
| Dry Scrubber Preheater | 118,614 | 229,303 | 311,544 |
| Dry Scrubber Pumps | 6,758 | 13,065 | 17,750 |
| Baghouse | 112,125 | 336,375 | 560,625 |
| Stack | 33,425 | 72,120 | 103,122 |
| I.D. Fan | 42,903 | 87,624 | 122,130 |
| Fuel Tanks | $ 155,957 | $ 301,494 | $ 409,127 |
| Solids Hopper | 102,909 | 286,709 | 481,207 |
| SUBTOTAL | $ 614,452 | $ 1,452,033 | $ 2,207,384 |
| Total Equipment Purchase Costs | $ 4,774,380 | $13,119,726 | $21,280,238 |
| Installation (40%) | 1,909,752 | 5,247,890 | 8,512,045 |
| Instrumentation (13%) | 620,669 | 1,705,564 | 2,766,431 |
| Piping (31%) | 1,480,058 | 4,067,115 | 6,596,874 |
| Electrical (10%) | 477,438 | 1,311,973 | 2,128,024 |
| SUBTOTAL | $ 9,262,297 | $24,452,268 | $41,283,662 |
| DESIGN (32%) | 2,963,935 | 8,144,726 | 13,210,772 |
| Total Capital Equipment | $12,226,232 | $33,596,994 | $44,494,433 |

TABLE D-7. SYSTEM PERSONNEL REQUIREMENTS

| Operator | Personnel/Shift Agent Rate | | | | |
|---|---|---|---|---|---|
| | 100 | 400 | 1000 | 3000 | 5000 |
| Control Room | 1 | 1 | 1 | 2 | 2 |
| Dissolution Tanks | 2 | 2 | 4 | 6 | 8 |
| Pumps, Blowers, Roasters | 1 | 1 | 2 | 3 | 3 |
| Outside | 1 | 1 | 2 | 3 | 3 |
| Supervision | 1 | 1 | 1 | 1 | 1 |
| General Maintenance | 1 | 1 | 2 | 3 | 5 |
| Machining | | | | 1/3 | 1/3 |
| Inventory | | | | 1/3 | 1/3 |
| Analytical | 1 | 1 | 1 | 2 | 2 |
| Instrumentation | 1/3 | 1/3 | 2/3 | 1 | 1 |
| Total/Shift | 8-1/3 | 8-1/3 | 13-2/3 | 21-2/3 | 25-2/3 |
| Shifts/Day | x3 | x3 | x3 | x3 | x3 |
| Person Years/Year | 25 | 25 | 41 | 65 | 77 |
| Rate | x$50,000 | x$50,000 | x$50,000 | x$50,000 | x$50,000 |
| Labor Costs/Year | $1,250,000 | $1,250,000 | $2,050,000 | $3,250,000 | $3,850,000 |

disposal in a hazardous landfill operation which would cost \$205/ton[26]. Annual spare parts costs were assumed to be 6 percent of the installed capital equipment costs. Summaries of the other operating cost estimates for single sites are shown in Table D-8 while collocation estimates can be found in Table D-9.

Production Time. Summaries of the single and collocated site production times required to dispose of the inventory categories can be found in Tables D-10 and D-11, respectively. Production years were determined in the same manner as the baseline.

Life Cycle Operating Costs. The production years for the inventory categories computed previously were used to compute the life cycle operating costs for each of three single site and three collocation site throughputs. The methodology outlined in the baseline was followed except that this concept does not require change outs and so the associated down time was deleted. The incurred single site life cycle operating costs are shown respectively in Tables D-12, D-13, and D-14 for 100, 400, and 1000 lb/hr of agent throughput. Collocation costs incurred at 1000, 3000 and 5000 lb/hr agent throughput rates are shown in Tables D-15, D-16, and D-17.

Development Costs. To fully develop this concept, it will be necessary to perform both bench-scale and pilot-scale experiments to resolve the knowledge gaps that have previously been identified. Estimates of the type and cost of the experimental and design studies that would be required are shown in Table D-18. These include the design, construction, and operation of 40 lb/hr of agent pilot plant operating on a single dissolution tank. The cost estimate for this facility was scaled directly from the previously operating plant estimates.

TABLE D-8. OTHER DIRECT COSTS - SINGLE SITE

| Item Usage Cost | Agent Feed Rate 100 lb/hr | 400 lb/hr | 1000 lb/hr |
|---|---|---|---|
| Water x$10^6$ gal/yr - \$0.53/1000 gal | 81 | 325.8 | 815 |
| COST | \$42,930 | \$172,674 | \$431,950 |
| Electric x$10^6$ kwh/yr - \$0.05/kwh | 0.21 | 0.85 | 2.13 |
| Yearly Cost | \$10,500 | \$42,500 | \$106,500 |
| Fuel Oil - gal/year | 258,000 | 1,032,000 | 2,580,000 |
| Cost/Year at \$1.20/gal | \$309,600 | \$1,238,400 | \$3,096,000 |
| $Fe_2O_3$ Disposal x $10^6$ lb/yr | 3.91 | 15.64 | 39.10 |
| at \$5/ton | \$9,775 | \$39,100 | \$97,750 |
| Caustic (in 10 wt% sol.) x $10^6$ lb/yr | 0.28 | 1.1 | 2.8 |
| Cost \$300/ton | \$42,000 | \$165,000 | \$420,000 |
| NaCl Disposal (solid) x $10^6$ lb/yr | 0.41 | 1.62 | 4.05 |
| Cost \$205/ton | \$42,025 | \$166,050 | \$415,125 |
| 20 wt% HCl Makeup x $10^6$ lb/yr | 0.89 | 3.56 | 8.90 |
| Cost \$35/ton | \$15,525 | \$62,300 | \$155,750 |
| Spare Parts (6% Capital Costs) | \$109,148 | \$304,085 | \$733,574 |
| TOTAL OTHER DIRECT COSTS | \$581,552 | \$2,190,108 | \$5,456,649 |

TABLE D-9. OTHER DIRECT COSTS - COLLOCATED SITE

| Item Usage Cost | Agent Feed Rate | | |
|---|---|---|---|
| | 1000 lb/hr | 3000 lb/hr | 5000 lb/hr |
| Water x $10^6$ Gal/Yr | 815 | 2445 | 4075 |
| Cost at $0.53/1000 Gal | $431,950 | $1,295,550 | $2,159,250 |
| Electric x $10^6$ kwh/Yr | 2.13 | 6.39 | 10.65 |
| Cost at 0.05 kwh | $106,500 | $319,500 | $532,500 |
| Fuel Oil Gal/Yr | 2,580,000 | 7,740,000 | 12,900,000 |
| Cost at $1.20/gal | $3,096,000 | $9,288,000 | $15,480,000 |
| $Fe_2O_3$ Disposal x $10^6$ lb/yr | 39.10 | 117.3 | 195.5 |
| | $97,750 | $293,250 | $487,500 |
| Caustic x $10^6$ lb/yr | 2.8 | 8.25 | 13.75 |
| Cost at $300/ton | $420,000 | $1,237,500 | $2,062,500 |
| NaCl Disposal x $10^6$ lb/yr | 4.05 | 12.15 | 20.25 |
| Cost at $205/ton | $415,125 | $1,295,375 | $2,075,625 |
| HCl Makeup x $10^6$ lb/yr | 8.90 | 26.7 | 44.5 |
| Cost at $35/ton | $155,750 | $467,250 | $778,750 |
| Spare Parts (6% Capital) | $733,574 | $2,015,820 | $3,269,666 |
| TOTAL OTHER DIRECT COSTS | $5,456,645 | $16,212,295 | $26,845,791 |

TABLE D-10. THERMAL PROCESS OPERATING TIME - SINGLE SITE

| Munition Category | Munition Type | Inventory | Through-put Per Hour | | | System Availability | Production Years | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | 100 lb/hr | 400 lb/hr | 1000 lb/hr | | 100 lb/hr | 400 lb/hr | 1000 lb/hr |
| A | M-55 Rockets | 80,000 | 9.3 | 37.4 | 93.5 | 0.79 | 2.18 | 0.545 | 0.22 |
| | M-23 Mines | 20,000 | 9.5 | 38.1 | 95.2 | 0.79 | 0.53 | 0.13 | 0.054 |
| | SUBTOTAL | | | | | | 2.71 | 0.67 | 0.27 |
| B/C | Mortars | 50,000 | 16.7 | 66.7 | 166.7 | 0.79 | 0.75 | 0.18 | 0.076 |
| | 105 mm Projectiles | 50,000 | 62.5 | 250.0 | 625.0 | 0.79 | 0.21 | 0.054 | 0.022 |
| | 155 mm Projectiles | 50,000 | 15.4 | 61.5 | 153.8 | 0.79 | 0.82 | 0.21 | 0.087 |
| | 8" Projectiles | 50,000 | 6.9 | 27.6 | 69.0 | 0.79 | 1.83 | 0.46 | 0.185 |
| | SUBTOTAL | | | | | | 3.61 | 0.91 | 0.37 |
| D | Bombs | 800 | 0.4 | 1.8 | 4.6 | 0.79 | 0.50 | 0.11 | 0.044 |
| | Ton Containers/ Spray Tanks | 200 | 0.1 | 0.3 | 0.7 | 0.79 | 0.50 | 0.16 | 0.076 |
| | SUBTOTAL | | | | | | 1.0 | 0.27 | 0.12 |

TABLE D-11. THERMAL PROCESS OPERATING TIME - COLLOCATED SITE

| Munition Category | Munition Type | Inventory | Through-put Per Hour | | | System Availability | Production Years | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | 1000 lb/hr | 3000 lb/hr | 5000 lb/hr | | 1000 lb/hr | 3000 lb/hr | 5000 lb/hr |
| A | M-55 Rockets | 800,000 | 93.5 | 286.4 | 467.3 | 0.79 | 2.17 | 0.71 | 0.43 |
| | M-23 Mines | 200,000 | 95.2 | 285.7 | 476.2 | 0.79 | 0.53 | 0.17 | 0.11 |
| | SUBTOTAL | | | | | | 2.70 | 0.84 | 0.54 |
| B/C | Mortars | 500,000 | 166.7 | 500.0 | 833.3 | 0.79 | 0.76 | 0.25 | 0.15 |
| | 105 mm Projectiles | 500,000 | 625.0 | 1875.0 | 3125.0 | 0.79 | 0.96 | 0.06 | 0.04 |
| | 155 mm Projectiles | 500,000 | 153.8 | 465.5 | 769.2 | 0.79 | 0.82 | 0.27 | 0.17 |
| | 8" Projectiles | 500,000 | 69.0 | 206.9 | 344.8 | 0.79 | 1.83 | 0.61 | 0.37 |
| | SUBTOTAL | | | | | | 4.37 | 1.19 | 0.73 |
| D | Bombs | 8,000 | 4.6 | 13.6 | 22.7 | 0.79 | 0.44 | 0.15 | 0.09 |
| | Ton Containers/ Spray Tanks | 2,000 | 0.7 | 2.0 | 3.3 | 0.79 | 0.72 | 0.25 | 0.15 |
| | SUBTOTAL | | | | | | 1.16 | 0.40 | 0.24 |

TABLE D-12. LIFE CYCLE OPERATING COSTS - SINGLE SITE
(100 LB/HR)

| Period | Rate, Labor $/Yr | Rate, Other $/Yr | Rate, Duration | Total Cost |
|---|---|---|---|---|
| Eq Acceptance | $ 416,667 | $ 193,851 | 0.50 | $ 305,259 |
| Training | 1,250,000 | 290,776 | 0.50 | 770,388 |
| Inventory Item A | 1,250,000 | 581,552 | 2.71 | 4,963,506 |
| Inventory Item B/C | 1,250,000 | 581,552 | 3.61 | 6,611,903 |
| Inventory Item D | 1,250,000 | 581,552 | 1.0 | 1,831,552 |
| Shutdown | 416,667 | 193,851 | 0.50 | 305,259 |
| Total Duration Operations Costs | | | | $14,787,867 |

TABLE D-13. LIFE CYCLE OPERATING COSTS - SINGLE SITE
(400 LB/HR)

| Period | Rate, Labor $/Yr | Rate, Other $/Yr | Duration | Total Cost |
|---|---|---|---|---|
| Eq Acceptance | $ 416,667 | $ 730,036 | 0.5 | $ 573,352 |
| Training | 1,250,000 | 1,095,055 | 0.5 | 1,172,528 |
| Inventory Item A | 1,250,000 | 2,190,109 | 0.67 | 2,308,803 |
| Inventory Item B/C | 1,250,000 | 2,190,109 | 0.91 | 3,130,499 |
| Inventory Item D | 1,250,000 | 2,190,109 | 0.27 | 928,829 |
| Shutdown | 416,667 | 730,036 | 0.50 | 573,352 |
| Total Duration Operations Costs | | | | $ 8,683,433 |

TABLE D-14. LIFE CYCLE OPERATING COSTS - SINGLE SITE
(1000 LB/HR)

| Period | Rate, Labor $/Yr | Rate, Other $/Yr | Duration | Total Cost |
|---|---|---|---|---|
| Eq Acceptance | $ 683,333 | $1,828,883 | 0.50 | $ 1,256,108 |
| Training | 2,050,000 | 2,743,325 | 0.50 | 2,396,663 |
| Inventory Item A | 2,050,000 | 5,456,649 | 0.27 | 2,026,795 |
| Inventory Item B/C | 2,050,000 | 5,456,649 | 0.37 | 2,777,460 |
| Inventory Item D | 2,050,000 | 5,456,649 | 0.12 | 900,798 |
| Shutdown | 683,333 | 1,828,883 | 0.50 | 1,256,108 |
| Total Duration Operations Costs | | | | $10,613,932 |

TABLE D-15. LIFE CYCLE OPERATING COSTS - COLLOCATED SITE
(1000 LB/HR)

| Period | Rate, Labor $/Yr | Rate, Other $/Yr | Duration | Total Cost |
|---|---|---|---|---|
| Eq Acceptance | $ 683,333 | $1,828,883 | 0.5 | $ 1,256,108 |
| Training | 2,050,000 | 2,743,325 | 0.5 | 2,396,663 |
| Inventory Item A | 2,050,000 | 5,456,649 | 2.70 | 20,267,952 |
| Inventory Item B/C | 2,050,000 | 5,456,649 | 4.37 | 32,804,056 |
| Inventory Item D | 2,050,000 | 5,456,649 | 1.16 | 8,707,713 |
| Shutdown | 683,333 | 1,828,883 | 0.5 | 1,256,108 |
| Total Duration Operations Costs | | | | $66,688,600 |

TABLE D-16. LIFE CYCLE OPERATING COSTS - COLLOCATED SITE
(3000 LB/HR)

| Period | Rate, Labor $/Yr | Rate, Other $/Yr | Duration | Total Cost |
|---|---|---|---|---|
| Eq Acceptance | $1,083,333 | $5,404,082 | 0.5 | $ 3,243,707 |
| Training | 3,250,000 | 8,106,123 | 0.5 | 5,678,061 |
| Inventory Item A | 3,250,000 | 16,212,245 | 0.84 | 16,348,286 |
| Inventory Item B/C | 3,250,000 | 16,212,245 | 1.19 | 23,160,072 |
| Inventory Item D | 3,250,000 | 16,212,245 | 0.40 | 7,784,898 |
| Shutdown | 1,083,333 | 5,404,082 | 0.5 | 3,243,707 |
| Total Duration Operations Costs | | | | $59,458,731 |

TABLE D-17. LIFE CYCLE OPERATING COSTS - COLLOCATED SITE
(5000 LB/HR)

| Period | Rate, Labor $/Yr | Rate, Other $/Yr | Duration | Total Cost |
|---|---|---|---|---|
| Eq Acceptance | $ 283,333 | $8,948,597 | 0.5 | $ 5,115,965 |
| Training | 3,850,000 | 13,422,922 | 0.5 | 8,636,461 |
| Inventory Item A | 3,850,000 | 26,845,791 | 0.54 | 16,575,727 |
| Inventory Item B/C | 3,850,000 | 26,845,791 | 0.73 | 22,407,927 |
| Inventory Item D | 3,850,000 | 26,845,791 | 0.24 | 7,366,990 |
| Shutdown | 1,283,333 | 8,948,597 | 0.5 | 5,115,965 |
| Total Duration Operations Costs | | | | $65,219,035 |

TABLE D-18. DEVELOPMENT COSTS

| | |
|---|---|
| Phase II - Bench Scale | |
| Concept Refinement | $ 30,000 |
| Acid Dissolution Studies | 100,000 |
| Acid Decomposition Studies | 220,000 |
| Roasting Studies | 190,000 |
| Environmental Studies | 50,000 |
| Design Criteria Development | 120,000 |
| Phase II Design Plan & Reporting | 40,000 |
| Contingencies | 50,000 |
| TOTAL PHASE II DEVELOPMENT COSTS | $ 800,000 |
| Phase III - Pilot Studies | |
| Pilot Plan Design | $ 340,000 |
| Test Plans and Operations Procedures | 60,000 |
| Pilot Plant Construction | 1,356,000 |
| Pilot Plant Startup | 176,000 |
| Operator Training | 444,000 |
| Pilot Plant Operation | 1,057,000 |
| Test Report | 20,000 |
| Process Development Program | 600,000 |
| 30% Design Package | 400,000 |
| Subcontractors | 250,000 |
| Contingencies (20%) | 940,000 |
| TOTAL PHASE III DEVELOPMENT COSTS | $5,693,000 |
| TOTAL DEVELOPMENT COSTS | $6,443,000 |

E. Total Costs

The total of the estimated costs for all three single site and all three collocated sites are summarized in Tables D-19 and D-20, respectively.

F. Optimum Process Flow Rate

From an operation standpoint, the full capacity of the major process elements is achieved at a throughput of approximately 400 pounds/hour of agent. This is not suprising since this rate produce an acid recycle rate that closely matches the Dravo spcifications. As anticipated from these observations, no economy of scale is observed. A further demonstration of this fact can be seen in the cost curves (Figures D-4 and D-5). Since a minimum collocated cost had not been observed at 1000 lb/hr throughput, life cycle costs for a 400 lb/hr were estimated in the following manner. The costs for processing each of the inventory categories for the 400 lb/hr single site summarized in Table D-13 were multiplied by 10 to represent the larger inventory and the single site and collocated site costs for startup, training, and shutdown were assumed to be the same. The life cycle operating costs for a 400 lb/hr collocated sit were so computed to be $66,001,242. The capital equipment, Facility and development costs were assumed to be the same bringing the total costs to $78,294,996. These numbers have been included in the cost curves and indicate that the optimum processing rate is approximately 400 lb/hr of agent whether single or collocated. This is not too surprising since this rate matches well the optimized processing rate of the Dravo estimate. It might further be noted that the estimated sum of the capital and facility costs for a 400 lb/hr facility ($5,850,754) also compares favorably with the Dravo turnkey estimate.

These estimates of the total life cycle cost indicate that, processing at this optimum flow rate, it would cost $20,977,187 to destroy a single site and $78,294,996 to destroy a collocated site

TABLE D-19. TOTAL COST ESTIMATES - SINGLE SITE

| Cost Item | Agent Rate (lb/hr) 100 lb/hr | 400 lb/hr | 1000 lb/hr |
|---|---|---|---|
| Facility Costs | $ 596,100 | $ 782,675 | $ 1,803,500 |
| Capital Equipment Costs | 1,819,138 | 5,068,079 | 12,226,232 |
| Life Cycle Operations Costs | 14,787,867 | 8,683,433 | 10,613,932 |
| Development Costs | 6,443,000 | 6,443,000 | 6,443,000 |
| TOTAL COSTS | $23,646,100 | $20,977,187 | $31,086,664 |

TABLE D-20. TOTAL COST ESTIMATES - COLLOCATED SITE

| Cost Item | Agent Rate (lb/hr) 1000 lb/hr | 3000 lb/hr | 5000 lb/hr |
|---|---|---|---|
| Facility Costs | $ 1,817,750 | $ 5,062,500 | $ 8,138,050 |
| Capital Equipment Costs | 12,226,232 | 33,596,994 | 54,494,433 |
| Life Cycle Operations Costs | 66,688,600 | 59,458,731 | 65,219,035 |
| Development Costs | 6,443,000 | 6,443,000 | 6,443,000 |
| TOTAL COSTS | $87,170,000 | $104,560,000 | $134,290,000 |

FIGURE D-4

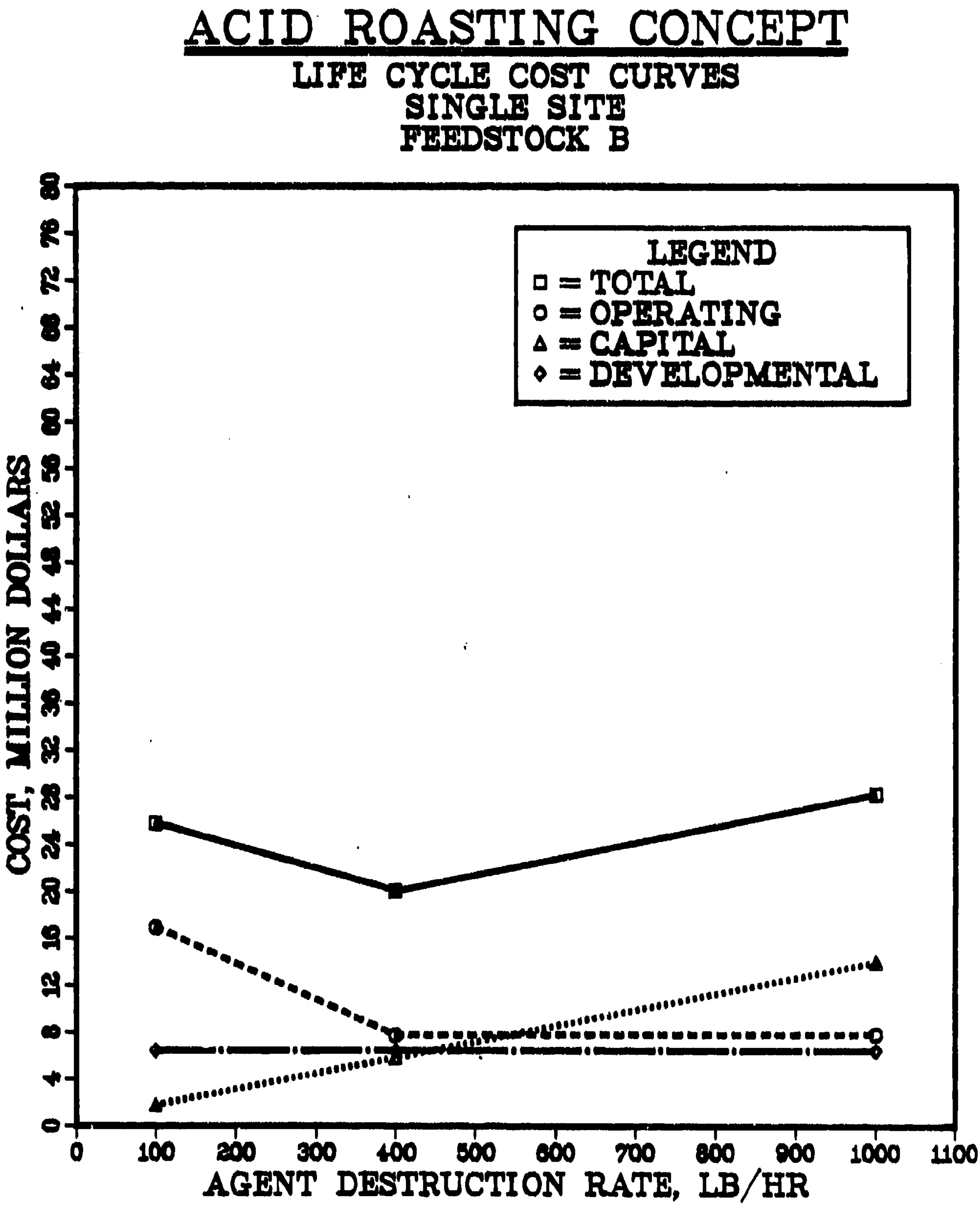
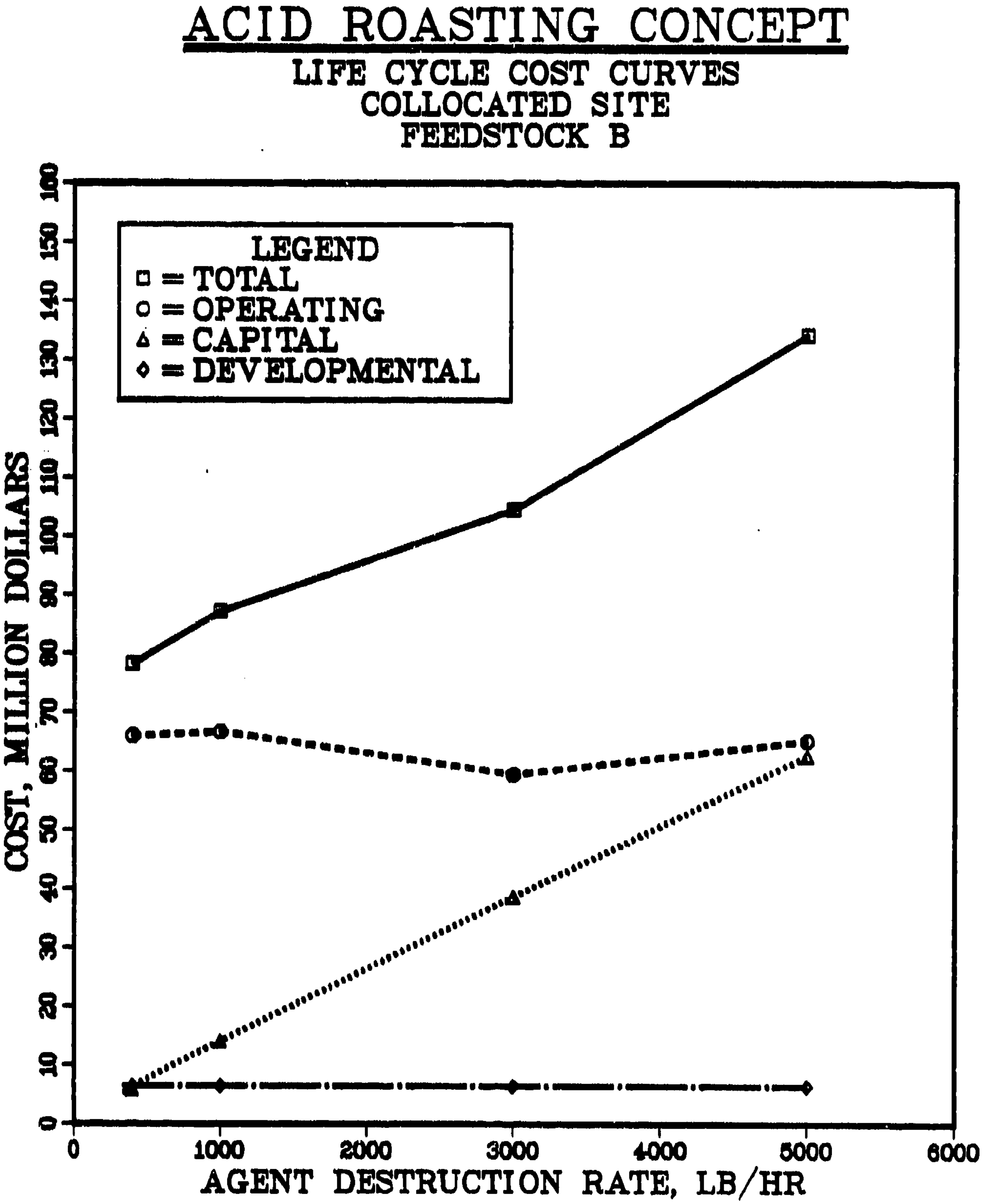

ACID ROASTING CONCEPT
LIFE CYCLE COST CURVES
SINGLE SITE
FEEDSTOCK B
LEGEND
□ = TOTAL
○ = OPERATING
△ = CAPITAL
◇ = DEVELOPMENTAL
COST, MILLION DOLLARS
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
72
76
80
0
100
200
300
400
500
600
700
800
900
1000
1100
AGENT DESTRUCTION RATE, LB/HR

FIGURE D-5


ACID ROASTING CONCEPT
LIFE CYCLE COST CURVES
COLLOCATED SITE
FEEDSTOCK B
LEGEND
□ = TOTAL
○ = OPERATING
△ = CAPITAL
◇ = DEVELOPMENTAL
COST, MILLION DOLLARS
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
0
1000
2000
3000
4000
5000
6000
AGENT DESTRUCTION RATE, LB/HR

As has been previously predicated, blast containment has not been incorporated in this conceptual design. The dissolution system could easily be converted to blast containment by utilizing small blast containment spheres as dissolution tanks. At a processing rate of 400 lb of agent/hour, 40 such spheres could be required. This modification would add $1.0M to the capital equipment costs, $1.6M to the facility costs, and might require 20 additional materials handlers increasing the life cycle labor costs by $10M. Such a modification therefore would only increase the total life cycle costs for a 400 lb/hour single site facility from $20.98M to $33.58 M.

While the munition unpack costs must still be added to the sums before they can be compared with the baseline costs of $101,000,000 and $355,000,000, it is obvious that implementation of this concept offers the opportunity for a significant cost savings.

## G. Operating Time

The operating time required for each munition category was discussed previously while developing the operating costs. The total operating time required to destroy the inventory at the processing rates of interest are summarized in Table D-21. From this table it can be seen that, processing at the optimum throughput of 400 lb/hour it would require 3.35 years to demilitarize a single site and 20 years to demilitarize a collocated site.

TABLE D-21. OPERATING TIME

| Agent Rate lb/hr | Operating Year |
|---|---|
| **Single Site** | |
| 100 | 8.82 |
| 400 | 3.35 |
| 1000 | 2.26 |
| **Collocated Site** | |
| 400 | 20 |
| 1000 | 9.73 |
| 3000 | 3.93 |
| 5000 | 3.01 |

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APPENDIX E

# ENGINEERING AND ECONOMIC ANALYSIS - ROTARY KILN

# APPENDIX E

## ENGINEERING AND ECONOMIC ANALYSIS - ROTARY KILN

Appendix E contains two rotary kiln concepts. The first concept is a large rotary kiln and the second concept is a proportional rotary kiln. The two concepts are presented separately.

## Engineering Analysis - Large Rotary Kiln

### A. System Concept Description

The large rotary kiln concept consists of one large rotary kiln without lifting flites or auger that will incinerate all agents, explosives, and dunnage. The kiln is large enough to handle all metal parts and is sufficient in length to decontaminate the metal parts. The size is based on handling ton containers and spray tanks and will handle agent feed rates up to 5000 lb/hr.

All materials are fed to the rotary kiln at the burner end through an inclined feed chute equipped with an air lock. The decontaminated metal parts and residue are discharged into the base of the vertical afterburner chamber and are removed by a conveyor from the bottom of the liquid seal tank maintained at the bottom of the afterburner chamber.

The flow diagram of the system is shown in Figure E-1. The system is operated at negative pressure by an induced draft fan included in the baghouse portion of the flow diagram. Operation of the system at negative pressure eliminates possible leaks of chemical agent or vapors during their incineration.

The overall system mass balance is compiled in Table E-1 and the overall system heat balance is compiled in Table E-2.

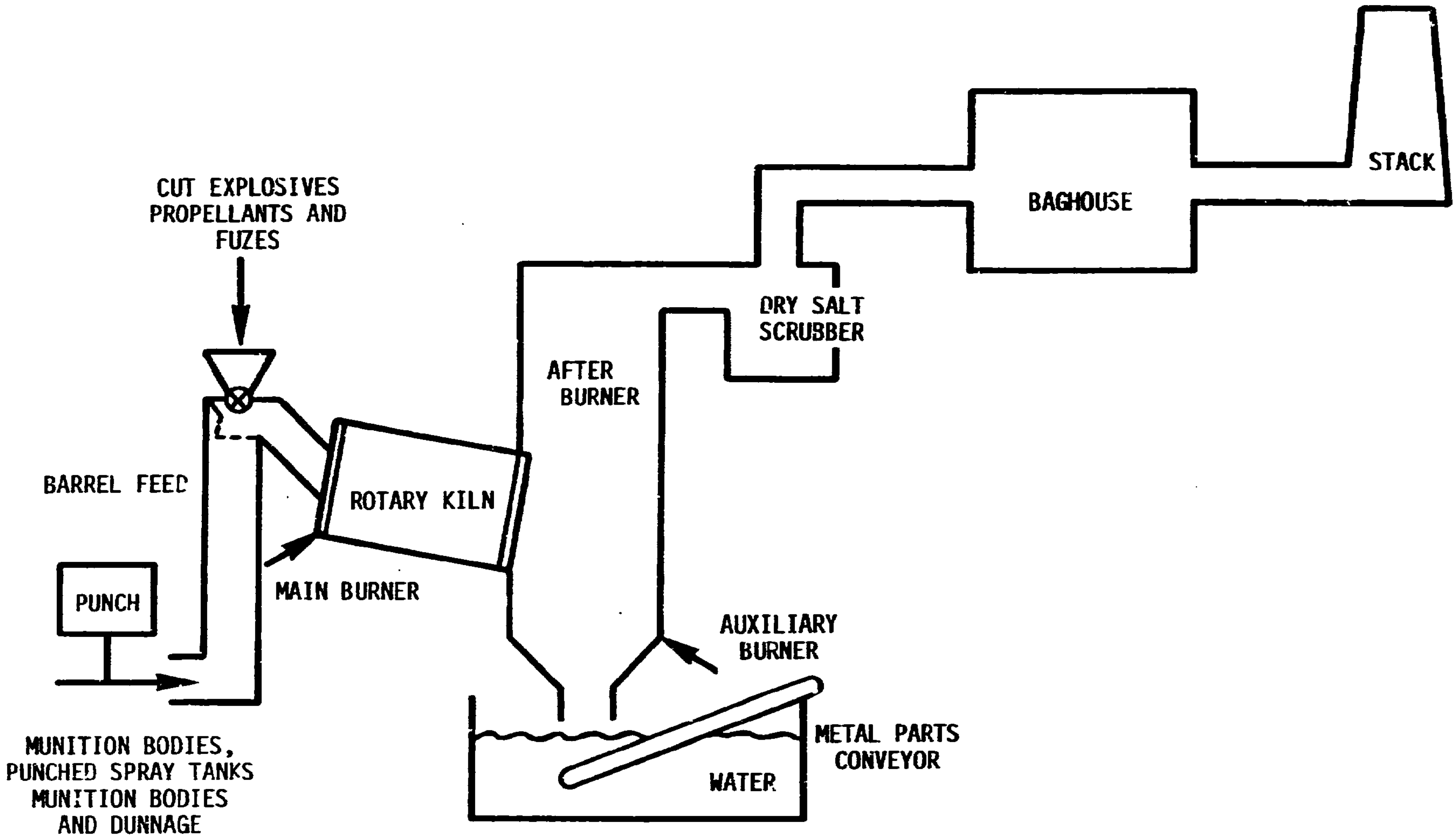


FIGURE E-1. LARGE ROTARY KILN SYSTEM CONCEPT

TABLE E-1. LARGE ROTARY KILN SYSTEM
MASS BALANCE
400 LB/HR AGENT FEED RATE

| Material | lb/hr |
|---|---|
| **IN** | |
| Wood | 650 |
| GB | 400 |
| Explosive | 250 |
| Fuel Oil (486 gal) | 3,506 |
| Air | 145,260 |
| Water | 40,770 |
| Metal | 2,050 |
| NaOH | 686 |
| TOTAL | 193,572 |
| **OUT** | |
| Flue gas w/water | 190,388 |
| Salts and Particulate | 1,134 |
| Metal | 2,050 |
| TOTAL | 193,572 |

TABLE E-2. LARGE ROTARY KILN SYSTEM
HEAT BALANCE
400 LB/HR AGENT FEED RATE

IN

| Material In | HHV | Btu/hr |
|---|---|---|
| Wood | 8,500 | 5,525,000 |
| Explosive | 5,400 | 1,350,000 |
| GB | 10,073 | 4,029,200 |
| #2 Fuel Oil | 142,000 (per gal) | 69,012,000 |
| TOTAL | | 79,916,200 |

OUT

| Material Out | Cp | ΔT,F | Btu/hr |
|---|---|---|---|
| Water in flue gas* | 0.50 | 1,530 | 46,680,820 |
| Flue gas | 0.25 | 330 | 12,343,485 |
| Metal | 0.11 | 1,530 | 345,015 |
| Salts & Particulate | 0.25 | 330 | 80,850 |
| Spent Salt* | 0.25 | 1,730 | 370,080 |
| Heat Losses | by difference | | 20,466,030 |
| TOTAL | | | 79,916,200 |

* Includes heat of vaporization or heat of fusion.

## B. System Feed Requirements

The requirements of the system for the burstered munitions are that the explosive be removed from the munition and the agent cavity open (feedstock e). For non-burstered munitions only the agent cavity must be opened (feedstock c). The dunnage may need some size reduction to permit feeding into the rotary kiln. Also, if there are any combustible items that have a cross-sectional area of much over 2 inches by 4 inches, these items may need size reduction to completely ashify the combustible during its residence time in the kiln.

## C. Pollution Abatement System

The current plan is to use baseline technology for the pollution control system. This will consist of a spray dry scrubber followed by a baghouse, induced draft fan and stack. The particulate generated from this system will be collected in the baghouse and drummed and stored. The salts will be dry and will contain heavy metals. If the salts can be certified agent free there may be the possibility of disposal in a hazardous landfill.

## D. Ultimate Disposal

The majority of the materials that remain to be disposed of after the incineration of the chemical agent and its related materials in the rotary kiln are as follows: decontaminated metal scrap, wood ash and dry salts generated in the pollution control system.

The metal scrap can be sold as scrap as has been done at CAMDS and RMA. It may need to be separated from wood ash and/or slag that it will be mixed with while being processed in the rotary kiln. This separation may only require a conveyor with a webbed belt that will allow the larger pieces of material, the metal scrap, to be transferred to its destination.

The wood ash will be collected in the liquid seal or the baghouse depending on the size of the ash particles and the gas velocities through the system. The larger particles that are not carried by the hot flue gases to the baghouse will fall from the discharge point of the rotary kiln and be collected in the liquid seal. Ash will settle to the bottom of the liquid seal vessel where it can be removed periodically and landfilled.

The dry salt and wood ash carryover to the baghouse will be drummed and stored as at CAMDS. If the salt can be certified agent free then the salts could be landfilled at an appropriate site.

## E. System Concept Advantages

The large rotary kiln system is a simple system to operate because it consists of one furnace and an afterburner that will handle all munitions in the appropriate feedstock. The system is easy to operate as a result of few moving parts and has few items that require service.

The munitions do not need to be drained of agent because the kiln will thermally download the agent from the munitions after the agent cavities have been opened. The system also has potential for post demil application because rotary kilns are commonly used for waste disposal of liquids, sludges, and solids.

## F. System Concept Disadvantages

Reducing the throughput of the large rotary kiln requires auxiliary fuel to maintain operating temperature. The size of the rotary kiln is fixed to allow for ton containers and spray tanks to be processed in the rotary kiln. This results in high gas throughputs through the entire system with little change due to a change in the feedrate of agent and related materials. Therefore, the system is better utilized at the higher agent throughput rates.

The rotary kiln system cannot handle detonations of munitions. This would result in equipment down time. The system can handle fuzes.

## G. System Concept Knowledge Gaps

Major system knowledge gaps are refractory life due to chemical attack and abrasion from the munitions, and feeding and discharge systems required to handle ton containers, bombs, and spray tanks.

## H. Safety

The rotary kiln system is safe. The system operates at negative pressure to eliminate leaks and the system operates cocurrently to maximize agent vapor exposure to the combustion conditions of the rotary kiln. The liquid seal provides a blast attenuation dampener in the event of an explosion and also acts as a pressure relief valve.

## I. Likelihood of Developments Within Five Years

Rotary kilns have been used for years for the disposal of toxic and hazardous materials such as pesticides, herbicides, PCB's, and dioxins. They have also been used for demilitarization of explosives and conventional munitions. The development of a large kiln to handle chemical agents and related materials involves scale-up of the feed and discharge systems, determining the correct refractory and operating conditions. The likelihood of development of a rotary kiln system within 5 years is very great.

J. Scalability

The system is the same size up to an agent feedrate of 5000 pounds per hour due to restraints placed on the system to handle ton containers and spray tanks.

K. Degree of Technical Risk

The projected size of the rotary kiln is state of the art. However, the current feed and discharge systems will need to be changed to handle ton containers and spray tanks. The current feed systems handle 55 gallon drums. The changes for the bulk items are not envisioned to be large. The degree of technical risk for this system is very low.

L. RAM Factors

The calculations are attached in Appendix L. Availability factor used for the economic calculations was 0.859.

M. Materials Compatibility

The materials compatibility problems are similar to the baseline system. There are corrosive flue gases as a result of the incineration of the agents. One additional compatibility problem which the deactivation furnace does not have is the abrasion of the rotary kiln refractory due to the munition bodies in the kiln rolling against the refractory.

N. Energy Requirements and Source

Since the rotary kiln size is fixed so that ton containers and spray tanks can be processed it has a fixed heat load range that must be maintained by fuel or the materials being incinerated.

Therefore, the fuel usage of the large rotary kiln is inversely proportional to the agent feed rate. The higher agent feed rates require less fuel oil to maintain the rotary kiln operating temperature due to the amount of heat released from the materials being incinerated.

Electrical power is needed to operate the kiln, feed and discharge systems and the pollution control system. The largest portion of the electrical power is needed for the pollution control system due to the large induced draft fan.

## O. Ease of Operation

Due to the fact that the thermal system consists of only one furnace system, the complexity of the thermal system is minimized. The furnace system has no complex moving parts and is an inherently simple system. One furnace system handling all munitions reduces the complexity of materials handling by minimizing possible handling routes.

The flexibility of the system is only limited by large detonable items which may result in equipment damage. The system also has applications after demilitarization for many types of wastes such as sludges, liquids, and solids. The operability is good because of its simplicity and flexibility.

## Economic Analysis - Large Rotary Kiln

### General Assumptions Made for Economic Analysis of Large Rotary Kiln

- Kiln size is constant
- Constant firing rate - 80 MMBtu/Hr
- Feed configuration is e (explosive downloaded, agent cavity opened)
- Kiln will handle all material
- Used baseline costs where components remained the same
- System availability is based on thermal system only (thermal system includes ultimate disposal and pollution control equipment)

### A. Single Site Facility Costs

Kiln. Constant size kiln results in constant size room 95' x 35' for all feed rates, which includes feed, kiln, afterburner. Cost is $400/sq. ft. Total cost is $1,330,000.

Scrap Handling. At a feed rate of 100 lb/hr agent produces 512.5 lb/hr metal scrap. Dunnage is 100 percent wood.

| Scrap | Agent Rate |
|---|---|
| 512 | 100 lb/hr |
| 2050 | 400 lb/hr |
| 5125 | 1000 lb/hr |
| 15,400 | 3000 lb/hr |
| 25,670 | 5000 lb/hr |

Baseline cost at 400 lb/hr is $133,200. Baseline cost at 3000 lb/hr is $350,100.

$$133{,}200 \ \left(\frac{100}{400}\right)^{.6} = \$57{,}980$$

$$133,200 \left(\frac{1000}{400}\right)^{.6} = \$230,820$$

$$350,100 \left(\frac{5000}{3000}\right)^{.6} = \$475,670.$$

<u>Salt and Drum Storage</u>. Baseline $150,880.

For a single site the total salt storage should be the same if the same type of Pollution Control System (PCS) is used so for a single site the cost remains the same for varying rates. For collocated the cost is $397,290.

<u>APC Pad</u>. Baseline 2500 scfm capacity
Space required 2500 ft$^2$ at $6250

For kiln system which will have a fairly constant fluegas flowrate regardless of the agent feed rate. The 80 MMBtu kiln PCS is rated for 57,000 SCMH ( 25,000 scfm).

$$\$6250\ (10)^{.6} = \$24,880$$

<u>Bulk Item Furnace</u>. Not needed in this system.

<u>Fuel Tank Pad</u>. Baseline fuel pad has 2 10'x25' (1963.5 ft$^3$), 14700 gal tanks and 1320 ft$^2$ at $3300.

The furnace is fixed at a rate of 80 MMBtu/hr. This requires 563 gallons per hour fuel oil at 142,000 Btu/gal (3,378,000 gal/year at 24 hours a day for 250 days a year).

However, the downtime must be factored in. Using the baseline of 0.65 availability reduces the oil usage to 2,195,700 gal/year. In addition the fuel oil usage will be reduced by the fuel value of the agent, dunnage and explosive.

#Fuel oil, 7.21 lb/gal

At 100 lb/hr the fuel value of the material is

| lb/hr | HHV | Btu/hr |
|---|---|---|
| 100 GB | 10,073 Btu/hr | 1,007,300 |
| 62.5 Exp. | 5,400 | 337,500 |
| 162.5 Wood | 8,500 | 1,381,250 |
| TOTAL | | 2,726,050 |

$(2{,}726{,}050)\left(\frac{1}{142{,}000}\right)(0.65)(20)(250) = 62392$ gal/year reduction in oil

2,195,700 - 62392 = 2,133,308 gal/year needed for 100 lb/hr.

| lb/hr | HHV | Btu/hr |
|---|---|---|
| (400) | (10073) | |
| (250) | (5400) | |
| (650) | (8500) | |
| TOTAL | | 10,579,200<br>242,130 gal/yr |

2,195,700 - 242,130 = 1,953,570 gal/year needed for 400 lb/hr.

| lb/hr | HHV | Btu/hr |
|---|---|---|
| (1000) | (10073) | |
| (625) | (5400) | |
| (1625) | (8500) | |
| TOTAL | | 27,260,500<br>623,920 gal/yr reduction |

2,195,700 - 623,920 = 1,571,780 gal/year needed at 1000 lb/hr.

<u>3000 lb/hr</u>.

(3000)(10073) Total 75,759,000 Btu/hr

(1900)(5400) 1,733,920 gal/hr

(4900)(8500).

2,195,700 - 1,733,920 = 563,380 gal/hr needed.

4 tanks needed.

5000 lb/hr.

(5000)(10073) Total 126,265,000 Btu/hr
(3167)(5400)
(8167)(8500) 2,889,867 gal/hr.

This is more than required. Will need oil for furnace heat-up and will use

$$(4 \text{ hrs/day})(250 \text{ day/yr})(80 \times 10^6 \text{ Btu/hr})(142{,}000 \text{ Btu/gal})^{-1}$$

563,380 gal/hr.

This number is larger than for 3000 lb/hr. Will adjust for 3000 lb/hr also.

4 tanks needed.

The above calculations are summarized in Tables E-3 and E-4.

Each tank is estimated to hold 14,700 gal and baseline uses 64.4 gal/hr for a total of 322,000 gal/year.

(2) $\frac{2{,}138{,}143}{322000}$ 13 tanks needed on basis of same refilling frequency.

100) $(\frac{13}{2})$ (\$3300) = \$21,450

400) $(\frac{12}{2})$ (\$3300) = \$19,800

1000) $(\frac{10}{2})$ (\$3300) = \$16,500

3000) $(\frac{4}{2})$ (\$3300) = \$6,600

5000) $(\frac{4}{2})$ (\$3300) = \$6,600.

B. Capital Equipment

Kiln Furnace. Ford, Bacon & Davis/BKMI verbal quote for 80 MMBtu unit 15' x 45' includes feed system, retort, afterburner, and pollution control system.

TABLE E-3. SINGLE SITE FACILITY COSTS - LARGE ROTARY KILN

| Facility | Baseline, $ | 100 lb/hr | 400 lb/hr | 1000 lb/hr |
|---|---|---|---|---|
| Kiln Furnace Area | $ 528,000 | $1,330,000 | $1,330,000 | $1,330,000 |
| Scrap Handling | 133,200 | 57,980 | 133,200 | 230,820 |
| Salt and Drum Storage | 150,880 | 150,880 | 150,880 | 150,880 |
| APC Pad | 6,250 | 24,880 | 24,880 | 24,880 |
| Bulk Item Furnace Area | 236,700 | 0 | 0 | 0 |
| Fuel Tank Pad | 3,300 | 21,450 | 19,800 | 16,500 |
| TOTAL | $1,058,330 | $1,585,190 | $1,658,760 | $1,753,080 |

TABLE E-4. COLLOCATED SITE FACILITY COSTS - LARGE ROTARY KILN

| Facility | Baseline, $ 3000 lb/hr | 1000 lb/hr | 3000 lb/hr | 5000 lb/hr |
|---|---|---|---|---|
| Kiln Furnace Room | $1,384,000 | $1,330,000 | $1,330,000 | $1,330,000 |
| Scrap Handling Area | 350,100 | 230,820 | 350,100 | 475,670 |
| Salt & Drum Storage | 397,290 | 397,290 | 397,290 | 397,290 |
| APC Pad | 16,425 | 24,880 | 24,880 | 24,880 |
| Bulk Furnace Area | 622,800 | 0 | 0 | 0 |
| Fuel Tank Pad | 8,650 | 21,450 | 6,600 | 6,600 |
| TOTAL | $2,779,265 | $2,004,440 | $2,108,870 | $2,234,440 |

Total $12,000,000

Same system/unit used for all feedrates.

Air Heat Exchanger. Baseline 11,000 SCFM $800^0$ T

$(842 \text{ lb/min})(60)(800^0\text{F})(.27 \text{ Btu/lb}^0\text{F}) = 10{,}912{,}320$ Btu/hr at $200,000

Our case we need to remove 24MMBtu/hr from the room:

$$\$200{,}000\left(\frac{24}{11}\right)^{.6} = \$319{,}400.$$

Same for all feedrates.

Bulk Furnace & Exchanger. Not needed.

Storage Forklift. Adjusted from baseline.

Pollution Control. The system provided by BKMI has a pollution control system similar to baseline. The cost is one-half of the total system stated under the heading Kiln Furnace, above. $6,000,000.

Fuel Tanks. See Facility Costs.

2 tanks cost $36,000 - $18,000 each.

| | | |
|---|---|---|
| 100 | 13 tanks | $234,000 |
| 400 | 12 tanks | $216,000 |
| 1000 | 10 tanks | $180,000 |
| 3000 | 4 tanks | $ 72,000 |
| 5000 | 4 tanks | $ 72,000 |

Residue Truck. Adjusted from baseline.

The capital equipment costs are compiled in Tables E-5 and E-6.

TABLE E-5. SINGLE SITE EQUIPMENT COSTS - LARGE ROTARY KILN

| Equipment | Baseline, $ | 100 lb/hr | 400 lb/hr | 1000 lb/hr |
|---|---|---|---|---|
| Kiln Furnace | $ 7,000,000 | $ 6,000,000 | $ 6,000,000 | $ 6,000,000 |
| Air Heat Exchanger | 80,000 | 319,400 | 319,400 | 319,400 |
| Bulk Furnace | 9,000,000 | 0 | 0 | 0 |
| Air Heat Exchanger | 95,000 | 0 | 0 | 0 |
| Storage Fork Lift | 22,000 | 22,000 | 22,000 | 44,000 |
| Kiln Scrubber | 250,000 | 6,000,000 | 6,000,000 | 6,000,000 |
| Bulk Scrubber | 295,000 | 0 | 0 | 0 |
| Kiln Baghouse | 130,000 | 0 | 0 | 0 |
| Bulk Baghouse | 170,000 | 0 | 0 | 0 |
| Fuel Tanks | 36,000 | 234,000 | 216,000 | 180,000 |
| Residue Handling Truck | 65,790 | 65,790 | 65,790 | 131,580 |
| Subtotal | 17,143,790 | 12,641,190 | 12,623,190 | 12,674,980 |
| Design | 25% | 20% | 20% | 20% |
| Total Equipment | 21,429,740 | 15,169,430 | 15,147,830 | 15,209,980 |
| Total Capital | $22,488,070 | $16,754,620 | $16,806,590 | $16,963,060 |

TABLE E-6. COLLOCATED SITE EQUIPMENT COSTS - LARGE ROTARY KILN

| Equipment | Baseline, $ 3000 lb/hr | 1000 lb/hr | 3000 lb/hr | 5000 lb/hr |
|---|---|---|---|---|
| Kiln Furnace | $15,743,000 | $ 6,000,000 | $ 6,000,000 | $ 6,000,000 |
| Air Heat Exchanger | 200,000 | 319,400 | 319,400 | 319,400 |
| Bulk Furnace | 20,241,000 | 0 | 0 | 0 |
| Air Heat Exchanger | 230,000 | 0 | 0 | 0 |
| Storage Fork Lift | 44,000 | 44,000 | 44,000 | 66,000 |
| Kiln Scrubber | 625,000 | 6,000,000 | 6,000,000 | 6,000,000 |
| Bulk Scrubber | 715,000 | 0 | 0 | 0 |
| Kiln Baghouse | 400,000 | 0 | 0 | 0 |
| Bulk Baghouse | 520,000 | 0 | 0 | 0 |
| Fuel Tanks | 90,000 | 180,000 | 72,000 | 72,000 |
| Residue Handling Truck | 173,000 | 131,580 | 173,000 | 288,300 |
| Subtotal | 38,981,000 | 12,674,980 | 12,608,400 | 12,745,700 |
| Design | 25% | 20% | 20% | 20% |
| Total Equipment | 48,726,250 | 15,209,980 | 15,130,080 | 15,294,840 |
| Total Capital | $51,505,515 | $17,214,420 | $17,238,950 | $17,529,280 |

C. Operating Cost

Personnel Requirements.

Kiln - Based on vendor information.

Maintenance - Estimate.

Control Room - Estimate.

Pollution Abatement - Included under kiln.

Ultimate Disposal - Scaled from baseline, based on same rates.

Cost - $50,000/man year

The labor costs are summarized in Tables E-7 and E-8.

Direct Costs.

Water. Baseline 9.5 M gal/yr for 11,000 scfm.

$$9.5 \left(\frac{25,000}{11,000}\right) = 21.6 \text{ Mgal/yr.}$$

Same for all feedrates.

Electric. Will cost the same regardless of feedrate for kiln, heat exchanger, and scrubber.

| | | |
|---|---|---|
| Kiln | .18 MKwHr/yr | vendor information |
| Heat Exchanger | .50 | 1.6x |
| Scrubber | 4.80 | vendor information |
| Salt Eq. | below | will be ratioed. |

Baseline .46 + 76 = 1.22 for 400 lb/hr.

| | | |
|---|---|---|
| 100 | (100/400) (1.22) = 0.31 + 5.48 = | 5.79 |
| 400 | 1.22 + 5.48 = | 6.70 |
| 1000 | (1000/400) (1.22) = 3.10 + 5.48 = | 8.58 |

TABLE E-7. SINGLE SITE LABOR COSTS - LARGE ROTARY KILN

| Area | Personnel Requirements (men/shift) Agent Rate 100 lb/hr | Agent Rate 400 lb/hr | Agent Rate 1000 lb/hr |
|---|---|---|---|
| Kiln | 2 | 2 | 2 |
| Maintenance | 2 | 2 | 2 |
| Control Room | 1 | 1 | 1 |
| Pollution Abatement | (Included under kiln) | 1 | 1 |
| Ultimate Disposal | 2 | 4 | 6 |
| Total/Shift | 7 | 10 | 12 |
| Man years/year | 21 | 30 | 36 |
| Labor cost $/year at $50,000/man year | 1,050,000 | 1,500,000 | 1,800,000 |

TABLE E-8. COLLOCATED SITE LABOR COSTS - LARGE ROTARY KILN

| Area | Personnel Requirements (men/shift) Agent Rate 1000 lb/hr | Agent Rate 3000 lb/hr | Agent Rate 5000 lb/hr |
|---|---|---|---|
| Kiln | 2 | 2 | 2 |
| Maintenance | 2 | 2 | 2 |
| Control Room | 1 | 1 | 1 |
| Pollution Abatement | 1 | 2 | 3 |
| Ultimate Disposal | 6 | 10 | 14 |
| Total/Shift | 12 | 17 | 22 |
| Man years/year | 36 | 51 | 66 |
| Labor cost $/year at $50,000/man year | 1,800,000 | 2,550,000 | 3,300,000 |

| | | | |
|---|---|---|---|
| 3000 | | 3.22 + 5.48 = | 8.70 |
| 5000 | (5000/3000) = | 5.37 + 5.48 = | 10.85 |

The direct costs are compiled in Tables E-9 and E-10.

Changeout Costs. During changeout the kiln will be shut down. This will result in air pollution control, salt equipment and scrap handling to be shut down.

Water usage will be 0
Electric will be lighting only
Fuel oil will be for startup and shutdown
Spare parts and materials/supplies remain.

Assume startup takes 8 hours at 80 MMBtu/hr:

$$((80 \times 10^6)(8)/142{,}000)(1.20) = \$5{,}400$$

The startup fuel will be added to spare parts, materials/supplies. Lighting will be neglected. The spare parts and materials/supplies will be rated for the duration of the changeout. Will need electric and water during startup. Will use a cost of \$12 for electric and \$18 for water.

Electric $(30)(8)(0.05) = \$12.$
Water $\left[(21.6 \times 10^6)/(20)(250)\right] \quad (8)(\frac{.53}{1000}) = \$18.$

Kiln refractory cost is \$350,000 (vendor information)
Life expectancy is 2 years.
Will replace refractory at each changeout at the lower feedrates. Assumed at lowest feedrate the refractory life will be increased.
Changeout direct costs will be:

$$5400 + 18 + 12 + 350{,}000 = \$355{,}430.$$

TABLE E-9. SINGLE SITE OPERATION COSTS - LARGE ROTARY KILN

| Utility | Annual Usage/Cost | | |
|---|---|---|---|
| | Agent Rate 100 lb/hr | Agent Rate 400 lb/hr | Agent Rate 1000 lb/hr |
| Water, $10^6$ gal/yr ($.53/1000 gal) | 21.6<br>$ 11,450 | 21.6<br>11,450 | 21.6<br>11,450 |
| Electric, $10^6$ kwy/yr ($0.05/Kwh) | 5.79<br>$ 289,500 | 6.70<br>335,000 | 8.58<br>429,000 |
| Fuel, gal/yr ($1.20/gal) | 2,138,143<br>2,565,770 | 1,953,570<br>2,344,280 | 1,620,130<br>1,944,160 |
| Spare Parts, 6% (Capital Equipment) w/Design | $1,055,280 | 1,008,400 | 1,017,780 |
| Materials/Supplies, 10% Other Operating | $ 492,200 | 519,910 | 520,240 |
| Total Direct Costs $/yr | $4,364,200 | 4,219,040 | 3,922,630 |

TABLE E-10. COLLOCATED SITE OPERATION COSTS - LARGE ROTARY KILN

| Utility | Annual Usage/Cost | | |
|---|---|---|---|
| | Agent Rate 1000 lb/hr | Agent Rate 3000 lb/hr | Agent Rate 5000 lb/hr |
| Water, $10^6$ gal/yr | 21.6 | 21.6 | 21.6 |
| ($.53/1000 gal) | $ 11,450 | 11,450 | 11,450 |
| Electric, $10^6$ kwy/yr | 8.58 | 8.70 | 10.85 |
| ($0.05/Kwh) | $ 429,000 | 435,000 | 542,500 |
| Fuel, gal/yr | 1,620,130 | 563,380 | 563,380 |
| ($1.20/gal) | 1,944,160 | 676,060 | 676,060 |
| Spare Parts, 6% (Capital Equipment) w/Design | $ 912,600 | 907,800 | 917,690 |
| Materials/Supplies, 10% Other Operating | $ 509,720 | 458,030 | 544,770 |
| Total Direct Costs $/yr | $3,806,930 | 2,488,340 | 2,692,470 |

| | | |
|---|---|---|
| 100 lb/hr | (.17)(1,005,280 + 492,200) = $254,570 |
| 400 lb/hr | (.17)(1,008,400 + 519,910) = $259,810 |
| 1000 lb/hr | (.17)(1,017,780 + 520,240) = $261,460. |

At 100 lb/hr agent feed rate refractory will be changed during both changeouts.

254,570 + 355,430 = 610,000

1000 - 2 Refractory Changes/Repair

700,000 + 5430 + 241,790 = 947,220 (both)

3000 - 1 Refractory

350,000 + 5430 + 241,770 = 247,300 (1st)

597,200 (2nd)

5000 - 0 Refractory

5430 + 258,200 = 263,630 (both)

At 400 lb/hr agent feed rate refractory will be changed only once during the second changeout.

1st changeout 259,810 + 5430 = 265,240

2nd changeout 259,810 + 5430 + 350,000 = 615,240.

At 1000 lb/hr no refractory change/repair needed.

Changeout 261,460 + 5430 = 266,890.

## D. Development Costs

The development costs are listed in Table E-11.

## E. Total Cost

The total costs are compiled in Table E-12 through E-19. The plots of the cost curves are shown in Figures E-2 and E-3.

TABLE E-11. DEVELOPMENT COSTS - LARGE ROTARY KILN

| | | |
|---|---|---|
| Phase II | Lab Studies | |
| | Concept Refinement | $ 15,000 |
| | Volatilization and Operation Studies | 100,000 |
| | Refractory-Materials Compatibility Studies | 100,000 |
| | Environmental Studies | 100,000 |
| | Feed and Discharge Studies | 100,000 |
| | Seal Design | 50,000 |
| | Materials | 150,000 |
| | Subcontractors | 150,000 |
| | Contingency | 50,000 |
| | Preliminary Pilot Plant Design | 60,000 |
| | TOTAL PHASE II | $ 875,000 |
| Phase II | Pilot Plant Studies | |
| | Pilot Plant Design | $ 200,000 |
| | Test Plans, Operating Procedures | 50,000 |
| | Pilot Plant Construction | 1,105,000 |
| | Pilot Plant Start-Up | 145,000 |
| | Operator Training | 390,000 |
| | Operation | 869,000 |
| | Test Reports | 15,000 |
| | Process Development | 250,000 |
| | 30% Design Package | 250,000 |
| | Subcontractors | 500,000 |
| | Contingencies (20% of 3,774,000) | 755,000 |
| | TOTAL PHASE III | $4,529,000 |
| TOTAL DEVELOPMENT COSTS | | $5,404,000 |

TABLE E-12. SINGLE SITE TOTAL OPERATING COST - LARGE ROTARY KILN
(100 LB/HR)

| Period | Labor Cost/Year | Other Direct Cost/Yr | Duration, Yr | Total Cost |
|---|---|---|---|---|
| Eq Acceptance | 350,000 | 1,454,730 | 0.50 | 902,365 |
| Training & Sys | 1,050,000 | 2,182,100 | 0.50 | 1,616,050 |
| A | 1,050,000 | 4,364,200 | 2.49 | 13,481,360 |
| Change Out | 1,050,000 | 610,000 | 0.17 | 788,500 |
| B/C | 1,050,000 | 4,364,200 | 3.34 | 18,083,430 |
| Change Out | 1,050,000 | 610,000 | 0.17 | 788,500 |
| D | 1,050,000 | 4,364,200 | 0.94 | 5,089,350 |
| Shutdown | 350,000 | 1,454,730 | 0.50 | 902,365 |
| Total Life Operating Cost | | | 8.61 | $41,651,920 |

TABLE E-13. SINGLE SITE TOTAL OPERATING COST - LARGE ROTARY KILN
(400 LB/HR)

| Period | Labor Cost/Year | Other Direct Cost/Yr | Duration, Yr | Total Cost |
|---|---|---|---|---|
| Eq Acceptance | 500,000 | 1,406,350 | 0.50 | 953,175 |
| Training & Sys | 1,500,000 | 2,109,520 | 0.50 | 1,804,760 |
| A | 1,500,000 | 4,219,040 | 0.62 | 3,545,800 |
| Change Out | 1,500,000 | 265,240 | 0.17 | 520,240 |
| B/C | 1,500,000 | 4,219,040 | 0.83 | 4,746,800 |
| Change Out | 1,500,000 | 615,240 | 0.17 | 870,240 |
| D | 1,500,000 | 4,219,040 | 0.26 | 1,486,950 |
| Shutdown | 500,000 | 1,406,350 | 0.50 | 953,175 |
| Total Life Operating Cost | | | 3.55 | $14,881,140 |

TABLE E-14. SINGLE SITE TOTAL OPERATING COST - LARGE ROTARY KILN
(1000 LB/HR)

| Period | Labor Cost/Year | Other Direct Cost/Yr | Duration, Yr | Total Cost |
|---|---|---|---|---|
| Eq Acceptance | 600,000 | 1,307,540 | 0.50 | 953,770 |
| Training & Sys | 1,800,000 | 1,961,315 | 0.50 | 1,880,660 |
| A | 1,800,000 | 3,922,630 | 0.25 | 1,430,660 |
| Change Out | 1,800,000 | 266,890 | 0.17 | 572,890 |
| B/C | 1,800,000 | 3,922,630 | 0.34 | 1,945,690 |
| Change Out | 1,800,000 | 266,890 | 0.17 | 572,890 |
| D | 1,800,000 | 3,922,630 | 0.11 | 629,490 |
| Shutdown | 600,000 | 1,307,540 | 0.50 | 953,770 |
| Total Life Operating Cost | | | 2.54 | $ 8,939,820 |

TABLE E-15. SINGLE SITE COSTS - LARGE ROTARY KILN

| | Agent Feed Rate | | |
|---|---|---|---|
| | 100 lb/hr | 400 lb/hr | 1000 lb/hr |
| Capital | $16,754,620 | $16,806,590 | $16,963,060 |
| Operating | 41,651,920 | 14,881,140 | 8,939,820 |
| Development | 5,404,000 | 5,404,000 | 5,404,000 |
| Total Life Cycle Cost | $63,810,540 | $37,091,730 | $31,306,880 |

TABLE E-16. COLLOCATED SITE TOTAL OPERATING COST - LARGE ROTARY KILN (1000 LB/HR)

| Period | Labor Cost/Year | Other Direct Cost/Yr | Duration, Yr | Total Cost |
|---|---|---|---|---|
| Eq Acceptance | 600,000 | 1,268,980 | 0.50 | 934,490 |
| Training & Sys | 1,800,000 | 1,903,465 | 0.50 | 1,851,730 |
| A | 1,800,000 | 3,806,930 | 2.48 | 13,905,190 |
| Change Out | 1,800,000 | 947,220 | 0.17 | 1,253,220 |
| B/C | 1,800,000 | 3,806,930 | 3.34 | 18,727,150 |
| Change Out | 1,800,000 | 947,220 | 0.17 | 1,253,220 |
| D | 1,800,000 | 3,806,930 | 1.08 | 6,055,480 |
| Shutdown | 600,000 | 1,268,980 | 0.50 | 934,490 |
| Total Life Operating Cost | | | 8.74 | $44,914,970 |

TABLE E-17. COLLOCATED SITE TOTAL OPERATING COST - LARGE ROTARY KILN (3000 LB/HR)

| Period | Labor Cost/Year | Other Direct Cost/Yr | Duration, Yr | Total Cost |
|---|---|---|---|---|
| Eq Acceptance | 850,000 | 829,450 | 0.50 | 839,720 |
| Training & Sys | 2,550,000 | 1,244,170 | 0.50 | 1,897,090 |
| A | 2,550,000 | 2,488,340 | 0.82 | 4,131,440 |
| Change Out | 2,550,000 | 247,300 | 0.17 | 680,800 |
| B/C | 2,550,000 | 2,488,340 | 0.10 | 5,541,170 |
| Change Out | 2,550,000 | 597,200 | 0.17 | 1,030,700 |
| D | 2,550,000 | 2,488,340 | 0.37 | 1,864,190 |
| Shutdown | 850,000 | 829,450 | 0.50 | 839,720 |
| Total Life Operating Cost | | | 4.13 | $15,825,830 |

TABLE E-18. COLLOCATED SITE TOTAL OPERATING COST - LARGE ROTARY KILN (5000 LB/HR)

| Period | Labor Cost/Year | Other Direct Cost/Yr | Duration, Yr | Total Cost |
|---|---|---|---|---|
| Eq Acceptance | 1,100,000 | 897,490 | 0.50 | 998,750 |
| Training & Sys | 3,300,000 | 1,346,235 | 0.50 | 2,323,120 |
| A | 3,300,000 | 2,692,470 | 0.50 | 2,996,230 |
| Change Out | 3,300,000 | 263,470 | 0.17 | 824,630 |
| B/C | 3,300,000 | 2,692,470 | 0.67 | 4,014,950 |
| Change Out | 3,300,000 | 263,630 | 0.17 | 824,630 |
| D | 3,300,000 | 2,692,470 | 0.22 | 1,318,340 |
| Shutdown | 1,100,000 | 897,490 | 0.50 | 998,750 |
| Total Life Operating Cost | | | 3.23 | $14,299,400 |

TABLE E-19. COLLOCATED SITE COSTS - LARGE ROTARY KILN

| | Agent Feed Rate | | |
|---|---|---|---|
| | 1000 lb/hr | 3000 lb/hr | 5000 lb/hr |
| Capital | $17,214,420 | $17,238,950 | $17,529,280 |
| Operating | 44,914,970 | 16,825,830 | 14,299,400 |
| Development | 5,404,000 | 5,404,000 | 5,404,000 |
| Total Life Cycle Cost | $67,533,390 | $39,468,780 | $37,232,680 |

## F. Optimum Process Flow Rate

For single site operation the optimum process flowrate occurs at the highest agent feed rate, based on the total life cycle costs. The collocated site optimum process flowrate is at 5000 lb/hr which is the limiting process rate of the large rotary kiln. For a larger feed rate, a second kiln will be added which would raise costs. See Figures E-2 and E-3 for the cost curves.

## G. Operating Time

The munition feed time will be based on the amount of agent per munition, thermal system availability, munition inventory, operation days and hours per year (20 hours a day and 250 days a year). Also for the thermal system, it is assumed that there is no difference between burstered and nonburstered munitions.

| Munition | lb agent/munition |
|---|---|
| M55 Rockets | 10.7 lb/rocket |
| 105 mm | 1.6 |
| 155 mm | 6.5 |
| 8" | 14.5 |
| Bomb | 220.0 |
| Ton | 1500.0 |
| Mortars | 6.0 |
| Mines | 10.5 |
| Spray Tank | 1356.0 |

Throughput/hr.

80,000 M55's $(100 \text{ lb/hr})(\frac{1}{10.7} \text{ lb/munition})$

$(20 \text{ hr/day})(250 \text{ days/hr})(0.859)$

| | |
|---|---|
| 100 lb/year | 2.00 years |
| 400 lb/year | 0.50 years |
| 1000 lb/year | 0.20 years |

The same steps were done for the other munitions on a programmable calculator. The calculations are compiled in Tables E-20 and E-21.

FIGURE E-2

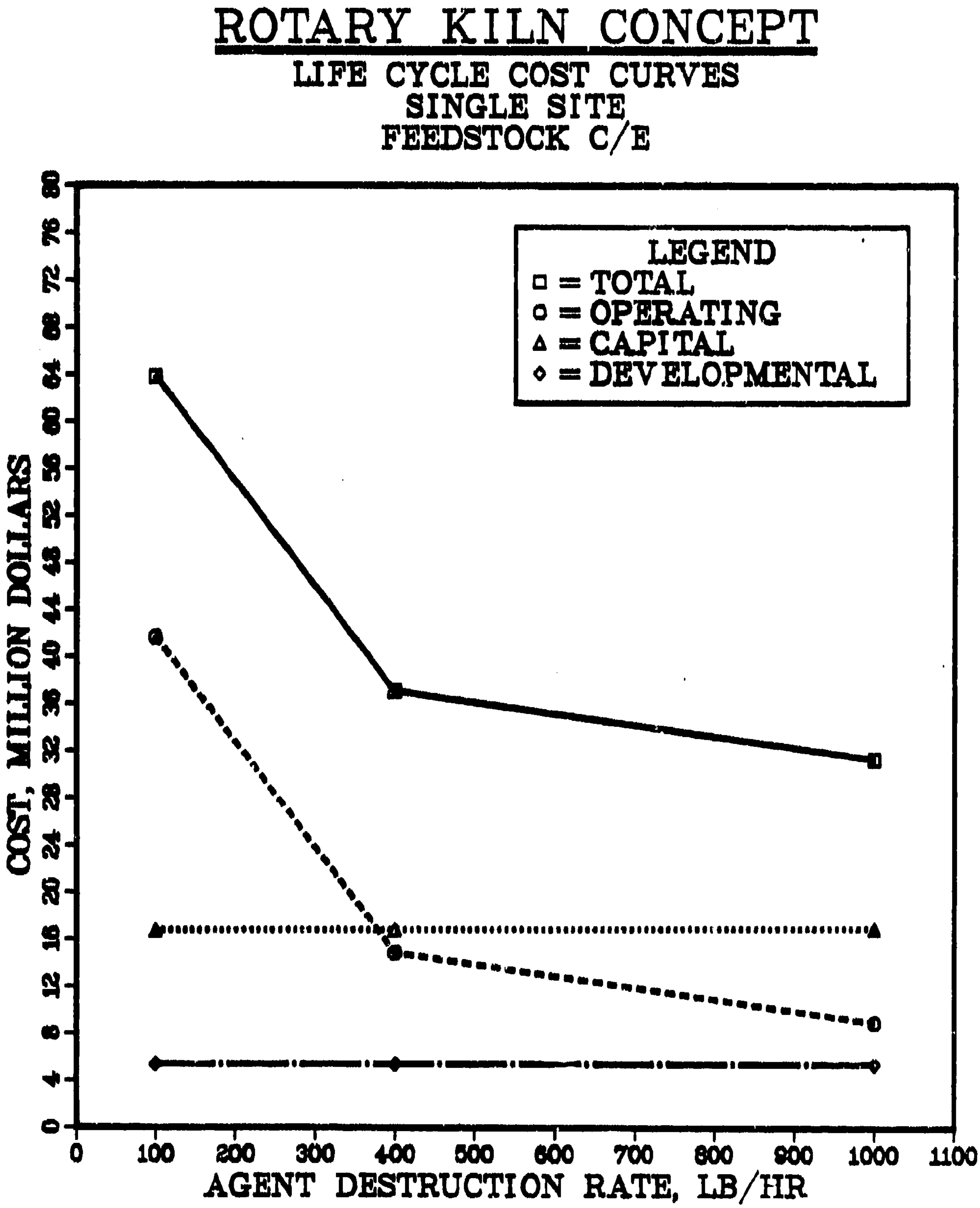
ROTARY KILN CONCEPT
LIFE CYCLE COST CURVES
SINGLE SITE
FEEDSTOCK C/E
LEGEND
□ = TOTAL
○ = OPERATING
△ = CAPITAL
◇ = DEVELOPMENTAL
COST, MILLION DOLLARS
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
72
76
80
0
100
200
300
400
500
600
700
800
900
1000
1100
AGENT DESTRUCTION RATE, LB/HR

FIGURE E-3

# ROTARY KILN CONCEPT

## LIFE CYCLE COST CURVES
## COLLOCATED SITE
## FEEDSTOCK C/E

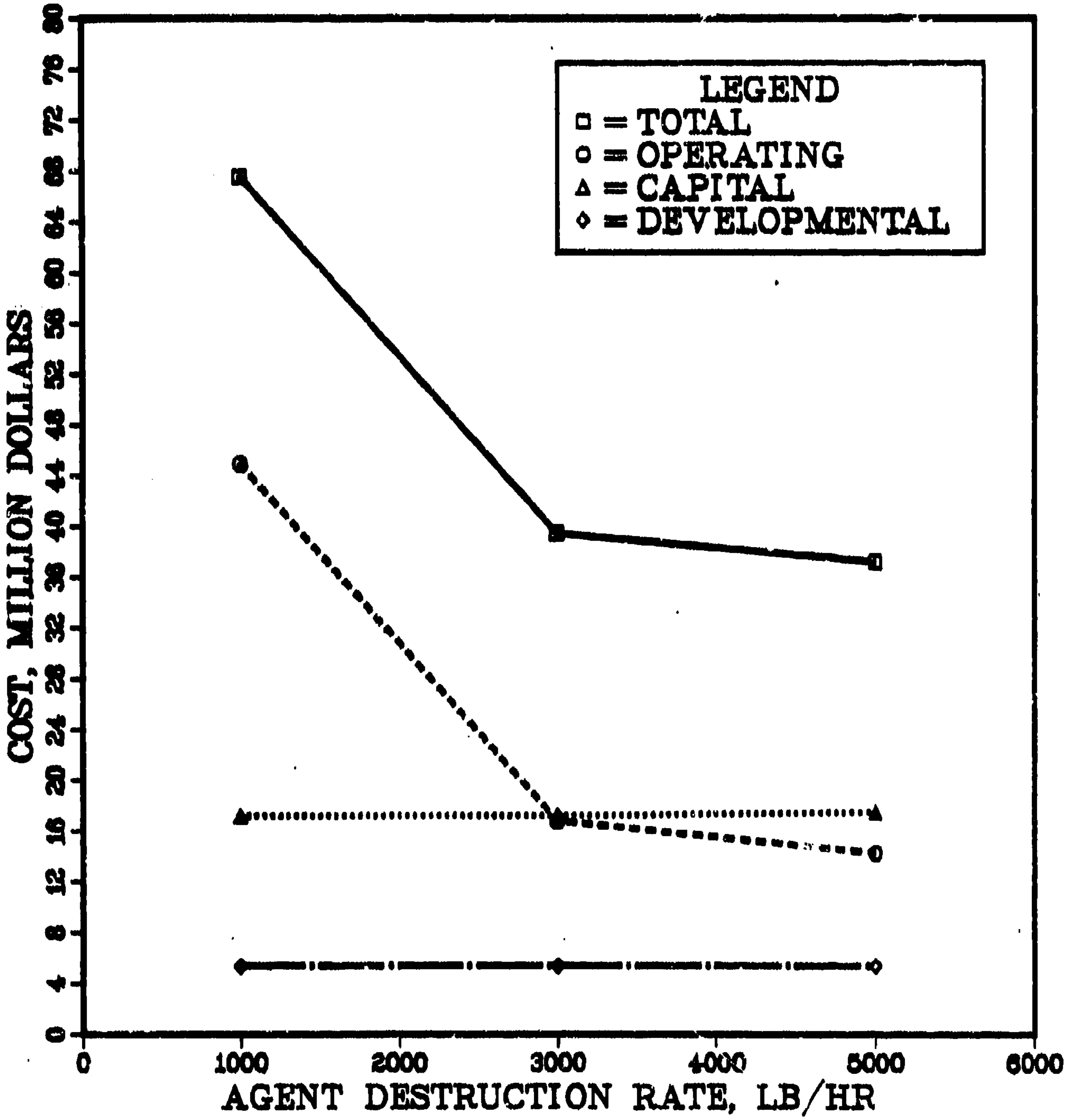

TABLE E-20. SINGLE SITE OPERATING TIME - LARGE ROTARY KILN

| Munition Category | Munition Type | Inventory | Through-put Per Hour 100 lb/hr | 400 lb/hr | 1000 lb/hr | System* Availability | Production Years 100 lb/hr | 400 lb/hr | 1000 lb/hr |
|---|---|---|---|---|---|---|---|---|---|
| A | M55 Rockets | 80,000 | 9.3 | 37.4 | 93.5 | 0.859 | 2.00 | 0.50 | 0.20 |
| | M23 Mines | 20,000 | 9.5 | 38.1 | 95.2 | 0.859 | 0.49 | 0.12 | 0.05 |
| B/C | Mortars | 50,000 | 16.7 | 66.7 | 166.7 | 0.859 | 0.70 | 0.17 | 0.07 |
| | 105 mm Projectiles | 50,000 | 62.5 | 250.0 | 625.0 | 0.859 | 0.19 | 0.05 | 0.02 |
| | 155 mm Projectiles | 50,000 | 15.4 | 61.5 | 153.8 | 0.859 | 0.76 | 0.19 | 0.08 |
| | 8" Projectiles | 50,000 | 6.9 | 27.6 | 69.0 | 0.859 | 1.69 | 0.42 | 0.17 |
| D | Bombs | 800 | 0.4 | 1.8 | 4.6 | 0.859 | 0.47 | 0.10 | 0.04 |
| | Ton Containers/ Spray Tanks | 200 | 0.1 | 0.3 | 0.7 | 0.859 | 0.47 | 0.16 | 0.07 |

* Based on Thermal System only.

TABLE E-21. COLLOCATED SITE OPERATING TIME - LARGE ROTARY KILN

| Munition Category | Munition Type | Inventory | Through-put Per Hour | | | System* | Production Years | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | 1000 lb/hr | 3000 lb/hr | 5000 lb/hr | Availability | 1000 lb/hr | 3000 lb/hr | 5000 lb/hr |
| A | M55 Rockets | 800,000 | 93.5 | 280.4 | 467.3 | 0.859 | 1.99 | 0.66 | 0.40 |
| | M23 Mines | 200,000 | 95.2 | 285.7 | 476.2 | 0.859 | 0.49 | 0.16 | 0.10 |
| B/C | Mortars | 500,000 | 166.7 | 500.0 | 833.3 | 0.859 | 0.70 | 0.23 | 0.14 |
| | 105 mm Projectiles | 500,000 | 625.0 | 1875.0 | 3125.0 | 0.859 | 0.19 | 0.06 | 0.04 |
| | 155 mm Projectiles | 500,000 | 153.8 | 465.5 | 769.2 | 0.859 | 0.76 | 0.25 | 0.15 |
| | 8" Projectiles | 500,000 | 69.0 | 206.9 | 344.8 | 0.859 | 1.69 | 0.56 | 0.34 |
| D | Bombs | 8,000 | 4.5 | 13.6 | 22.7 | 0.859 | 0.41 | 0.14 | 0.08 |
| | Ton Containers/ Spray Tanks | 2,000 | 0.7 | 2.0 | 3.3 | 0.859 | 0.67 | 0.23 | 0.14 |

* Based on Thermal System only.

## Engineering Analysis - Proportional Rotary Kiln

### A. System Concept Description

The proportional rotary kiln concept consists of one rotary kiln with the kiln volume scaled to the feed rate. This single kiln will incinerate all agent, explosive and dunnage but requires the feed material to be liquid or small enough to be handled by the rotary kiln. The larger the kiln the larger the solid feed material can be. The kiln length will be sufficient to decontaminate the metal parts.

All materials are fed to the rotary kiln at the burner end through an inclined fuel chute equipped with an air lock. Any liquids could be pumped into the kiln through an injection nozzle located beside the burner. The decontaminated metal parts and any residues are discharged into the base of the vertical afterburner chamber and are removed by a conveyor from the bottom of the liquid seal tank that is maintained at the bottom of the afterburner chamber.

The process and general flow diagram of the system is shown in Figure E-4. The system is operated at negative pressure by an induced draft fan included in the baghouse portion of the flow diagram. Operation of the system at negative pressure eliminates possible leaks of agent or vapors during their incineration. The overall system mass balance is compiled in Table E-22 and the overall system heat balance is compiled in Table E-23.

### B. System Feed Requirements

This system has been based on feed configuration h (mashed munitions - 6 inches or less). The advantage to feedstock h is that the rotary kiln size can be selected to match the feedrate instead of using a fixed size kiln to match the items being fed. This would result in more efficient fuel usage. At the higher feedrates the fundamental size can be increased to the limiting size of the rotary kiln. At a 5000-pounds per hour feedrate the kiln size is sufficient

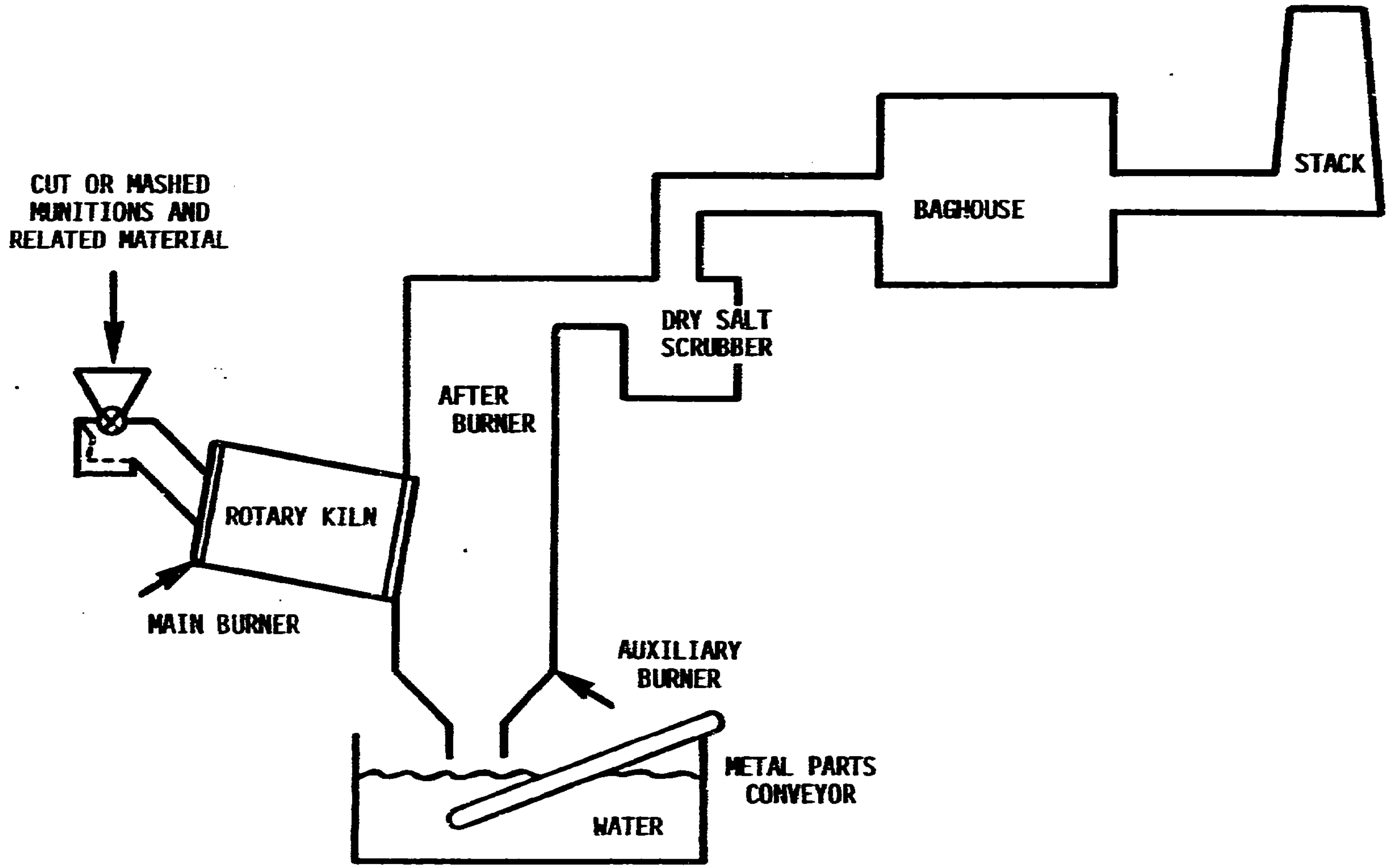


FIGURE E-4. PROPORTIONAL ROTARY KILN SYSTEM CONCEPT

TABLE E-22. PROPORTIONAL ROTARY KILN SYSTEM
MASS BALANCE
400 LB/HR AGENT FEED RATE

| Material | lb/hr |
|---|---|
| IN | |
| Wood | 650 |
| GB | 400 |
| Explosive | 250 |
| Fuel Oil (486 gal) | 55 |
| Air | 21,220 |
| Water | 6,110 |
| Metal | 2,050 |
| NaOH | 686 |
| TOTAL | 31,421 |
| OUT | |
| Flue gas w/water | 28,535 |
| Salts and Particulate | 836 |
| Metal | 2,050 |
| TOTAL | 31,421 |

TABLE E-23. PROPORTIONAL ROTARY KILN SYSTEM
HEAT BALANCE
400 LB/HR AGENT FEED RATE

IN

| Material In | HHV | Btu/hr |
|---|---|---|
| Wood | 8,500 | 5,525,000 |
| Explosive | 5,400 | 1,350,000 |
| GB | 10,073 | 4,029,200 |
| #2 Fuel Oil | 142,000 (per gal) | 1,093,400 |
| TOTAL | | 11,997,600 |

OUT

| Material Out | Cp | ΔT,F | Btu/hr |
|---|---|---|---|
| Water in flue gas* | 0.50 | 1,530 | 6,996,600 |
| Flue gas | 0.25 | 330 | 2,354,140 |
| Metal | 0.11 | 1,530 | 345,015 |
| Salts & Particulate | 0.25 | 330 | 68,970 |
| Metal | 0.11 | 1,530 | 345,015 |
| Heat Losses | by | difference | 2,232,875 |
| TOTAL | | | 11,997,600 |

* Includes heat of vaporization or heat of fusion.

to handle all bulk items. The size of the kiln at 400 pounds per hour should be sufficient to handle small projectile munitions in feedstock c for nonburstered and e for burstered (c - agent cavity open, e - explosive downloaded, agent cavity open). Combustible items that have a cross-sectional area of greater than 2 inches by 4 inches may need size reduction to completely ashify the combustible during its resident time in the kiln or the residence time of all materials will be driven by the required residence time to ashify the combustible.

This system will also handle feedstock g if the sawed pieces are small enough for the rotary kiln to handle.

## C. Pollution Abatement System

The current approach is to use baseline technology for the pollution control system. The baseline consists of a spray dry scrubber followed by a baghouse, induced draft fan and stack. The particulate generated from this system will be collected in the baghouse, drummed and stored. The salts will be dry and will contain heavy metals. If the salts can be certified agent free there may be the possibility of disposal in a hazardous landfill, otherwise, the salts must be stored. For the purpose of this study the salts were stored.

## D. Ultimate Disposal

The majority of the materials that remain after the incineration of the chemical agent and its related materials in the rotary kiln are as follows: decontaminated metal scrap, wood ash and dry salts generated in the pollution control system.

The metal scrap can be sold as scrap as has been done at CAMDS and RMA. It may need to be separated from the wood ash and/or slag that it will be mixed with upon being discharged from the rotary kiln. This separation may only require a conveyor with a webbed belt that will allow the larger pieces of material, the metal scrap, to be

transferred to its destination. The material that falls through the conveyor will be collected and landfilled.

The wood ash will be collected in the liquid seal or the baghouse depending on the size of the ash particles and the gas velocities through the system. The larger particles that are not carried by the hot flue gases to the baghouse will fall from the discharge point of the rotary kiln and be collected in the liquid seal. Ash will settle to the bottom of the liquid seal vessel where it can be removed periodically and landfilled.

The dry salt and wood ash carry over to the baghouse will be drummed and stored as at CAMDS.

## E. System Concept Advantages

The rotary kiln system is a simple system to operate because it consists of one furnace and an afterburner that will handle all munitions in feedstock g or h. The system is easy to operate as a result of few moving parts and has few items that require service.

As a result of feedstock size being small there is no large item handling system to feed the furnace or handle discharged materials. The system also has potential for post demil applications because rotary kilns commonly are used for waste disposal of liquids, sludges, and solids.

Since the system has few major knowledge gaps due to its state-of-the-art status, it might to be "fast-tracked" at only a minor increase in technical risk.

## F. System Concept Disadvantages

The rotary kiln system as it is used in this system cannot handle detonations of items larger than fuzes. The feedstock requires a large amount of preparation.

## G. System Concept Knowledge Gaps

The major rotary kiln system knowledge gap is refractory life due to chemical attack and abrasion from the metal.

## H. Safety

The rotary kiln system using feedstock g or h is very safe. The explosives are in small individual amounts and are not contained. Also the feed entering the kiln will enter at a uniform rate which will eliminates large surges of combustion gas leaving the kiln. The kiln will operate at negative pressure to eliminate system leaks. The system operates cocurrently to maximize agent vapor exposure to the combustion conditions of the rotary kiln. The liquid seal provides a blast attenuation damper in the event of an explosion.

## I. Likelihoou of Development Within Five Years

Rotary kilns have been used for years for the disposal of toxic and hazardous materials such as pesticides, herbicides, PCB's, and dioxins. They have also been used for demilitarization of explosives and conventional munitions. The development of the rotary kiln to handle chemical agents and related materials involves determining the correct refractory and operating conditions.

## J. Scalability

The rotary kiln system is very scalable. Rotary kilns of the size range needed for the 100 to 5000 pound per hour agent feedrates have been built in industry for other uses.

## K. Degree of Technical Risk

The technical risk for the rotary kiln system feeding cut or mashed munitions in small pieces, less than 10 inches is very low. There is much state-of-the-art experience with a multiplicity of feed materials in rotary kilns.

## L. RAM Factors

The calculations are attached in Appendix L. The overall thermal system availability factor is 0.881.

## M. Materials Compatibility

The materials compatibility problems are similar to the baseline system. One difference is that the rotary kiln has a refractory lining to keep the kiln wall at a low temperature and to protect the wall from the corrosive gases.

## N. Energy Requirements and Source

The energy usage of the rotary kiln is dependent upon size of the kiln. The larger the unit the more fuel usage. The fuel usage is low during incineration of the agent because there is sufficient heating value in the feed material to maintain the operating temperature. A pilot flame may be all that is required during operation. During idling conditions the fuel usage will increase to keep the refractory temperature hot; the temperature is estimated at 1200°F.

Electrical power is needed to operate the kiln, feed and discharge systems and the pollution control system. The largest portion of the electrical power is needed for the pollution control system due to the large induced draft fan.

O. Ease of Operation

The complexity of the thermal system is minimized since it consists of only one furnace. The furnace system itself has no complex moving parts and is an inherently simple system.

The system can handle all but large detonable items. It can handle fuzes, giving it a high degree of flexibility.

The operability is good because of its simplicity and flexibility. The number of personnel required to operate the rotary is small. The system is easy to start up and shut down.

## Economic Analysis - Proportional Rotary Kiln

### General Assumptions

All munitions and related materials are Feedstock h or g.

### A. Facility Costs

Kiln. The manufacturer uses a L/D ratio of 2 for the kiln size. The approximate kiln diameter is as follows:

| | | |
|---|---|---|
| 100 lb/hr | 3 Ft Diameter | 6 Ft Length |
| 400 lb/hr | 5 Ft Diameter | 10 Ft Length |
| 1000 lb/hr | 7 Ft Diameter | 14 Ft Length |
| 3000 lb/hr | 12 Ft Diameter | 24 Ft Length |
| 5000 lb/hr | 15 Ft Diameter | 30 Ft Length |

Will allow 5 feet each side of kiln, 10 feet for feed system, and 15 feet for AFB and scrap discharge.

| lb/hr | Room Sizes | | Cost |
|---|---|---|---|
| 100 | 13' x 31 | $400/ft^2$ | 161,200 |
| 400 | 15' x 35 | $400/ft^2$ | 210,000 |
| 1000 | 17' x 39 | $400/ft^2$ | 265,200 |
| 3000 | 22' x 49 | $400/ft^2$ | 431,200 |
| 5000 | 25' x 55 | $400/ft^2$ | 550,000 |

Scrap Handling.

Baseline cost at 400 lb/hr is $133,200.
Baseline cost at 3000 lb/hr is $350,100.

| lb/hr | $ | |
|---|---|---|
| 100 | 58,000 | $(100/400)^{.6} \times 133,200$ |
| 400 | 133,200 | |
| 1000 | 181,100 | $(1000/3000)^{.6} \times 350,100$ |
| 3000 | 350,100 | |
| 5000 | 475,700 | $(5000/3000)^{.6} \times 350,100$ |

<u>Salt and Drum Storage</u>. Will use baseline ultimate disposal. Regardless of feed rate, the total salts generated should be appoximately the same at completion time.

Single Site - \$150,880

Collocated Site - \$397,290

<u>APC Pad</u>.

| | | |
|---|---|---|
| Baseline | 400 lb/hr | 2500 $ft^2$ at \$2.5/$ft^2$ |
| | 3000 lb/hr | 6570 $ft^2$ at \$2.5/$ft^2$ |

$6250 \times (\frac{100}{400})^{.6}$ = \$2800 at 100 lb/hr

$16425 \times (\frac{1000}{3000})^{.6}$ = \$8500 at 1000 lb/hr

$16425 \times (\frac{5}{3})^{.6}$ = \$22,300 at 5000 lb/hr

<u>Bulk Item Furnace</u>. Not needed in this system.

<u>Fuel Tank Pad</u>. Dependent on Fuel Usage.

Assumptions: 10 percent supplemented fuel usage during use (Example: kiln rated at 40 MMBtu will use 4 MMBtu/hr of fuel). Will fire kiln at this rate during 4-Hr period per day and weekends.

100 lb/hr. 3 MMBtu/hr Unit.

$$\left(\frac{300,000 \text{ Btu/hr}}{142,000 \text{ Btu/gal}}\right)(24)(365) = 18,507 \text{ gal/yr}$$

Each tank from baseline is estimated to hold 14,700 gal. Baseline uses 322,000 gal/year. Tanks are filled monthly. Will use one-half sized tank.

$$\left(\frac{.5}{2}\right) 1320 = 330 \text{ ft}^2 - \$2.5/\text{ft}^2 \qquad \$900.$$

400 lb/hr. 11 MMBtu/hr Unit.

$$\left(\frac{1,100,000}{142,000}\right)(24)(365) = 66,186 \text{ gal/yr.}$$

One tank - 660 $ft^2$ - $1650.

1000 lb/hr. 28 MMBtu/hr. 168,473 gal/yr.
One tank per year - $1650.

3000 lb/hr. 83 MMBtu/hr. 512,028 gal/year.
Four tanks - 2640 $ft^2$ - $6600.

5000 lb/hr. 137 MMBtu/Hr. 845,155 gal/yr.
Six tanks - 3960 $ft^2$ - $9900.

The numbers calculated above are summarized in Tables E-24 and E-25.

## B. Capital Equipment

Kiln.

| Agent Feed Rate | Total Heat Release | Unit Cost, Millions* |
|---|---|---|
| 100 | 2.7 MMBtu/Hr | .7 |
| 400 | 10.9 MMBtu/Hr | 1.0 |
| 1000 | 27.3 MMBtu/Hr | 1.6 |
| 3000 | 82.1 MMBtu/Hr | 3.1 |
| 5000 | 136.8 MMBTU/Hr | .5 |

* CE Raymond Costs

The cost is a total package base price, it includes:

- Ram Feeder
- Kiln
- Liquid Firing Nozzles
- Afterburner
- Water Quench
- Packed Tower
- Neutralization System
- ID Fan
- Stack
- Emergency Stack
- Control Panel
- Controls
- Motor Control Center
- Sludge Lances
- Ash Removal
- Refractory

TABLE E-24. SINGLE SITE FACILITY COSTS - PROPORTIONAL ROTARY KILN

| Facility | 100 lb/hr | 400 lb/hr | 1000 lb/hr |
|---|---|---|---|
| Kiln Furnace Area | $161,200 | $210,000 | $265,200 |
| Scrap Handling | 58,000 | 133,200 | 181,100 |
| Salt and Drum Storage | 150,880 | 150,880 | 150,880 |
| APC Pad | 2,800 | 6,250 | 8,500 |
| Fuel Tank Pad | 900 | 1,650 | 1,650 |
| TOTAL | $373,780 | $501,980 | $607,330 |
| Baseline: $1,058,330 | | | |

TABLE E-25. COLLOCATED SITE FACILITY COSTS - PROPORTIONAL ROTARY KILN

| Facility | 1000 lb/hr | 3000 lb/hr | 5000 lb/hr |
|---|---|---|---|
| Kiln Furnace Area | $ 265,200 | $ 431,200 | $ 550,000 |
| Scrap Handling | 181,100 | 350,100 | 475,700 |
| Salt and Drum Storage | 397,290 | 397,290 | 397,290 |
| APC Pad | 8,500 | 16,425 | 22,300 |
| Fuel Tank pad | 1,650 | 6,600 | 9,900 |
| TOTAL | $ 853,740 | $1,201,615 | $1,455,190 |
| Baseline: $2,779,265 | | | |

Will use a factor of 40 percent for installation of equipment. Will not remove cost for quench, packed tower, neutralization system, and emergency stack.

Kiln System Costs, Installed

| Lb/Hr | Cost, Million Dollars |
|---|---|
| 100 | 0.98 |
| 400 | 1.40 |
| 1000 | 2.24 |
| 3000 | 4.34 |
| 5000 | 6.30 |

Air Heat Exchanger. Will size based on maximum of 30% heat losses.

| lb/hr | Heat Loss Btu/hr | $ |
|---|---|---|
| 100 | 810,000 | 42,000 |
| 400 | 3,300,000 | 97,700 |
| 1000 | 8,400,000 | 171,100 |
| 3000 | 24,900,000 | 328,300 |
| 5000 | 41,100,000 | 443,500 |

Baseline 10,900,000 Btu/hr at 200,000.

$$\$200,000 \left(\frac{810,000}{10,900,000}\right)^{.6} = 42,000.$$

Bulk Furnace & Exchanger. Not needed.

Storage Fork Lift. Same as baseline. Will adjust for feed rate.

Pollution Control. Will scale from baseline from RMDLwE furnace system.

Baseline

400 lb/hr = (250,000 + 130,000) = 380,000

3000 lb/hr = (625,000 + 400,000) = 1,025,000

| | | |
|---|---|---|
| 100 | $(\frac{100}{400})^{.6} \times 380{,}000 =$ | \$165,400 |
| 400 | | 380,000 |
| 1000 | $(\frac{1000}{3000})^{.6} \times 1{,}025{,}000 =$ | \$530,200 |
| 3000 | | 1,025,000 |
| 5000 | $(\frac{5000}{3000})^{.6} \times 1{,}025{,}000 =$ | 1,392,600/ |

Fuel Tanks. See Facility Costs for number of tanks. Tank cost - \$18,000 each.

| | | |
|---|---|---|
| 100 | ½ | 9,000 |
| 400 | 1 | 18,000 |
| 1000 | 1 | 18,000 |
| 3000 | 4 | 72,000 |
| 5000 | 6 | 108,000 |

The equipment costs are compiled in Tables E-26 and E-27.

## C. Operating Cost

Personnel Requirements.

| | 100 | 400 | 1000 | 3000 | 5000 |
|---|---|---|---|---|---|
| Kiln | 2 | 2 | 2/3 | 3 | 3 |
| Maintenance | 2 | 2 | 2 | 2 | 2 |
| Control Room | 1 | 1 | 1 | 1 | 1 |
| Pollution Abatement | 1 | 1 | 2 | 2 | 3 |
| Ultimate | 2 | 4 | 6 | 10 | 14 |
| Totals | 8 | 10 | 12/13 | 18 | 23 |

Based on vendor estimates and baseline numbers.

The labor costs are compiled in Tables E-28 and E-29.

TABLE E-26. SINGLE SITE EQUIPMENT COSTS - PROPORTIONAL ROTARY KILN

| Equipment | 100 lb/hr | 400 lb/hr | 1000 lb/hr |
|---|---|---|---|
| Kiln Furnace | $ 980,000 | $1,400,000 | $2,240,000 |
| Air Heat Exchanger | 42,000 | 97,700 | 171,100 |
| Storage Fork Lift | 22,000 | 22,000 | 44,000 |
| Kiln APC | 165,400 | 380,000 | 530,200 |
| Fuel Tanks | 9,000 | 18,000 | 18,000 |
| Residue Handling Truck | 65,790 | 65,790 | 131,580 |
| Subtotal | 1,284,190 | 1,983,490 | 3,134,880 |
| Design | 20% | 20% | 20% |
| Total Equipment | 1,541,030 | 2,380,190 | 3,761,860 |
| Total Capital | $1,914,810 | $2,882,170 | $4,369,190 |
| Baseline: $22,488,070 | | | |

TABLE E-27. COLLOCATED SITE EQUIPMENT COSTS - PROPORTIONAL ROTARY KILN

| Equipment | 1000 lb/hr | 3000 lb/hr | 5000 lb/hr |
|---|---|---|---|
| Kiln Furnace | $2,240,000 | $4,340,000 | $6,300,000 |
| Air Heat Exchanger | 171,100 | 328,300 | 443,500 |
| Storage Fork Lift | 44,000 | 44,000 | 66,000 |
| Kiln APC | 530,200 | 1,025,000 | 1,392,600 |
| Fuel Tanks | 18,000 | 72,000 | 108,000 |
| Residue Handling Truck | 131,580 | 173,000 | 288,300 |
| Subtotal | 3,134,880 | 5,982,300 | 8,598,400 |
| Design | 20% | 20% | 20% |
| Total Equipment | 3,761,860 | 7,178,760 | 10,318,080 |
| Total Capital | $4,615,600 | $8,380,375 | $11,773,270 |
| Baseline: $51,505,515 | | | |

TABLE E-28. SINGLE SITE LABOR COSTS
PROPORTIONAL ROTARY KILN

| Area | Personnel Requirements (men/shift) Agent Rate 100 lb/hr | Agent Rate 400 lb/hr | Agent Rate 1000 lb/hr |
|---|---|---|---|
| Kiln | 2 | 2 | 2 |
| Maintenance | 2 | 2 | 2 |
| Control Room | 1 | 1 | 1 |
| Pollution Abatement | 1 | 1 | 1 |
| Ultimate Disposal | 2 | 4 | 6 |
| Total/Shift | 8 | 10 | 12 |
| Man Years/Year | 24 | 30 | 36 |
| Labor Cost $/Year at $50,000/man year | 1,200,000 | 1,500,000 | 1,800,000 |

TABLE E-29. COLLOCATED SITE LABOR COSTS
PROPORTIONAL ROTARY KILN

| Area | Personnel Requirements (men/shift) Agent Rate 1000 lb/hr | Agent Rate 3000 lb/hr | Agent Rate 5000 lb/hr |
|---|---|---|---|
| Kiln | 3 | 3 | 3 |
| Maintenance | 2 | 2 | 2 |
| Control Room | 1 | 1 | 1 |
| Pollution Abatement | 2 | 2 | 3 |
| Ultimate Disposal | 6 | 10 | 14 |
| Total/Shift | 14 | 18 | 23 |
| Man Years/Year | 42 | 54 | 69 |
| Labor Cost $/Year at $50,000/man year | 2,100,000 | 2,700,000 | 3,450,000 |

Direct Costs.

Water. The water is required to cool the flue gases. Will assume 50% of heat released will need to be cooled with water, 30% is heat loss, and the balance goes out the stack.

$$1054 \text{ Btu/lb} \times 8.33 \text{ lb/gal} = 8780 \text{ Btu/gal}$$

| lb/hr | Heat | MMgal/yr | $/yr |
|---|---|---|---|
| 100 | $1.5 \times 10^6$ Btu/hr | 0.85 | 450 |
| 400 | $5.5 \times 10^6$ Btu/hr | 3.13 | 1660 |
| 1000 | $14.0 \times 10^6$ Btu/hr | 7.97 | 4220 |
| 3000 | $41.5 \times 10^6$ Btu/hr | 23.63 | 12520 |
| 5000 | $68.5 \times 10^6$ Btu/hr | 39.01 | 20680 |

Assumed 20 hours/day, 250 days/year.

Electric. MKw hr/yr.

| | 100 | 400 | 1000 | 3000 | 5000 |
|---|---|---|---|---|---|
| Kiln | 0.10 | .23 | .40 | .61 | .83 |
| Heat Exchanger | 0.06 | .15 | .31 | .51 | .69 |
| Scrubber | 0.40 | .92 | 1.59 | 2.42 | 3.29 |
| Salt Eq | 0.53 | 1.22 | 2.11 | 3.22 | 4.37 |
| TOTAL | 1.09 | 2.52 | 4.41 | 6.76 | 9.18 |

Used kiln power at 400 and 3000 lb/hr feed rate and scaled directly to other feed rates. Used .31 for heat exchanger at 1000 lb/hr, which was the same heat load as baseline and scaled accordingly. Added salt and scrubber power requirements for PBI and RMDLwE furnaces to get amounts for 400 and 3000 lb/hr and then scaled accordingly.

100 lb/hr.

Kiln $\left(\frac{100}{400}\right)^{.6}$ .23 = 0.10

| | | |
|---|---|---|
| Heat Exchanger | $(\frac{.8}{10.9})^{.6}$ .31 | = 0.06 |
| Scrubber | $(\frac{100}{400})^{.6}$ .92 | = 0.40 |
| Salt | $(\frac{100}{400})^{.6}$ 1.22 | = 0.53 |

<u>400 lb/hr.</u>

| | | |
|---|---|---|
| Heat Exchanger | $(\frac{3.3}{10.9})^{.6}$ .31 | = 0.15 |

<u>1000 lb/hr.</u>

| | | |
|---|---|---|
| Kiln | $(\frac{1000}{400})^{.6}$ .23 | = 0.40 |
| Heat Exchanger | $(\frac{24.9}{10.9})^{.6}$ .31 | = 0.51 |
| Scrubber | $(\frac{1000}{400})^{.6}$ .92 | = 1.59 |
| Salt | $(\frac{1000}{400})^{.6}$ 1.22 | = 2.11 |

<u>3000 lb/hr.</u>

| | | |
|---|---|---|
| Heat Exchanger | $(\frac{24.9}{10.9})^{.6}$ .31 | = 0.51 |

<u>5000 lb/hr.</u>

| | | |
|---|---|---|
| Kiln | $(\frac{5}{3})^{.6}$ .61 | = 0.83 |
| Heat Exchanger | $(\frac{41.1}{10.9})^{.6}$ .31 | = 0.69 |
| Scrubber | $(\frac{5}{3})^{.6}$ 2.42 | = 3.29 |
| Salt | $(\frac{5}{3})^{.6}$ 3.22 | = 4.37 |

<u>Fuel Oil</u>

See Fuel Tank Pad Calculations $1.2/gallon

| lb/hr | Fuel gal/yr | $/yr |
|---|---|---|
| 100 | 18,507 | 22,200 |
| 400 | 66,186 | 79,400 |
| 1000 | 168,473 | 202,200 |
| 3000 | 512,028 | 614,400 |
| 5000 | 845,155 | 1,014,200 |

Spare Parts. 6 percent capital equipment/year (includes design cost).

Material/Supplies. 10 percent other operating costs/year (includes personnel labor). The direct operating costs are compiled in Tables E-30 and E-31.

Change Out Costs. Assuming life of refractory in kiln is 2 years or greater depending on feedrate. Will change/replace refractory during change out if duration of operation has been greater than 2 years.

Refratory 4" - $10.52/ft^2$ (Guthrie)
1968 \$ M&S 273.1
1982 \$ M&S 746

$$(10.52)\left(\frac{746}{273.1}\right) = \$28.74/ft^2 \ (1982)$$

| Feedrate | Kiln Size D x L | Refractory Sq. Ft. | Cost |
|---|---|---|---|
| 100 | 3 x 6 | 57 | $ 1,630 |
| 400 | 5 x 10 | 157 | 4,510 |
| 1000 | 7 x 14 | 308 | 8,850 |
| 3000 | 12 x 24 | 905 | 26,000 |
| 5000 | 15 x 30 | 1414 | 40,630 |

During change out the kiln will be shut down. This will result in air pollution control, salt equipment, and scrap handling being idle. The only remaining costs will be spare parts and materials/supplies and some fuel during start-up. There will also be some electric and water costs during start-up but these costs are insiginificant. Eight hours start-up time assumed for all systems.

TABLE E-30. SINGLE SITE OPERATION COSTS - PROPORTIONAL ROTARY KILN

| Utility | Annual Usage/Cost Agent Rate 100 lb/hr | Agent Rate 400 lb/hr | Agent Rate 1000 lb/hr |
|---|---|---|---|
| Water, $10^6$ gal/yr ($.53/1000 gal) | 0.85<br>450 | 3.13<br>1,660 | 7.97<br>4,220 |
| Electric, $10^6$ KWH/Yr ($0.05/KWH) | 1.09<br>54,500 | 2.52<br>126,000 | 4.41<br>220,50 |
| Fuel Oil, Gal/yr ($1.20/gal) | 18,507<br>22,200 | 66,186<br>79,400 | 168,473<br>202,200 |
| Spare Parts, 6% Capital Equipment w/Design | 92,460 | 142,810 | 225,710 |
| Materials/Supplies, 10% Other Operating | 136,960 | 184,990 | 245,260 |
| Total Direct Costs $/yr | 306,570 | 534,860 | 897,890 |

TABLE E-31. COLLOCATED SITE OPERATION COSTS - PROPORTIONAL ROTARY KILN

| Utility | Annual Usage/Cost | | |
|---|---|---|---|
| | Agent Rate 1000 lb/hr | Agent Rate 3000 lb/hr | Agent Rate 5000 lb/hr |
| Water, $10^6$ gal/yr | 7.97 | 23.63 | 39.01 |
| ($.53/1000 gal) | 4,220 | 12,520 | 20,680 |
| Electric, $10^6$ KWH/Yr | 4.41 | 6.76 | 9.18 |
| ($0.05/KWH) | 54,500 | 126,000 | 220,50 |
| Fuel Oil, Gal/yr | 168,473 | 512,028 | 845,155 |
| ($1.20/gal) | 202,200 | 614,400 | 1,014,200 |
| Spare Parts, 6% Capital Equipment w/Design | 225,710 | 430,730 | 619,080 |
| Materials/Supplies, 10% Other Operating | 260,260 | 409,560 | 556,300 |
| Total Direct Costs $/yr | 912,890 | 1,805,210 | 2,669,260 |

100 lb/hr.

| | | |
|---|---|---|
| Refractory | | $ 1,630 |
| Spare Parts | (0.17)(92,460) | 15,718 |
| Materials/Supplies | (0.17)(136,960) | 23,283 |
| Fuel | (270,000)/(142,000)(8)(1.2) | 18 |
| TOTAL | 40,650 | |

Will need refractory replacement/repair each change out.

400 lb/hr.

| | | |
|---|---|---|
| Refractory | | $ 4,510 |
| Spare Parts | (.17)(142,810) | 24,278 |
| Materials/Supplies | (.17)(184,990) | 31,448 |
| Fuel | (1.09 x $10^6$)/142,000)(8)(1.2) | 74 |
| | | 60,310 (2nd) |
| | | 55,800 (1st) |

SS 1000 lb/hr.

| | | |
|---|---|---|
| Refractory | not needed | $ 8,850 |
| Spare Parts | (.17)(225,710) | 38,371 |
| Materials/Supplies | (.17)(245,260) | 41,694 |
| Fuel | (2.73 x $10^6$)/142,000)(8)(1.2) | 185 |
| | | 80,250 |

CS 1000 lb/hr.

| | | |
|---|---|---|
| Refractory | needed each change out | $ 8,850 |
| Spare Parts | (.17)(225,710) | 38,371 |
| Materials/Supplies | (.17)(260,260) | 44,244 |
| Fuel | (2.73 x $10^6$)/(142,000)(8)(1.2) | 185 |
| | | 91,650 |

CS 3000 lb/hr.

| | | |
|---|---|---|
| Refractory | needed second change out | $ 26,000 |
| Spare Parts | (.17)(430,730) | 73,224 |
| Materials/Supplies | (.17)(409,560) | 69,625 |
| Fuel | (18.21 x $10^6$)/142,000)(8)(1.2) | 555 |
| | | 169,400 (2nd) |
| | | 143,400 (1st) |

CS 5000 lb/hr.

| | | |
|---|---|---|
| Refractory | not needed | \$ 40,630 |
| Spare Parts | (.17)(619,080) | 105,244 |
| Materials/Supplies | (.17)(556,300) | 94,571 |
| Fuel | $(13.68 \times 10^6)/142,000)(8)(1.2)$ | 925 |
| | | 200,740 |

D. Development Costs

The developments costs are presented in Table E-32.

E. Total Cost

Total life cycle costs are given in Tables E-33 through E-40. Figures E-5 and E-6 present the total life cycle cost curves.

F. Optimum Process Flow Rate

The optimum process feed rate for the single site operation occurs near 400 lb/hr agent feed rate and the optimum feed rate for the collocated site occurs near 3000 lb/hr. These optimums are based on total life cycle costs. See Figures E-5 and E-6 for cost curves.

G. Operating Time

Operating times are given in Tables E-41 and E-42.

TABLE E-32. DEVELOPMENT COSTS - PROPORTIONAL ROTARY KILN

| | | |
|---|---|---|
| Phase II | Lab Studies | |
| | Concept Refinement | $ 15,000 |
| | Refractory-Materials Compatibility Studies | 100,000 |
| | Environmental Studies | 100,000 |
| | Materials | 150,000 |
| | Subcontractors | 100,000 |
| | Contingency | 40,000 |
| | Preliminary Pilot Plant Design | 40,000 |
| | TOTAL PHASE II | $ 545,000 |
| Phase III | Pilot Plant Studies | |
| | Pilot Plant Design | $ 100,000 |
| | Test Plans, Operating Procedures | 50,000 |
| | Pilot Plant Construction | 1,105,000 |
| | Pilot Plant Start-Up | 145,000 |
| | Operator Training | 390,000 |
| | Operation | 869,000 |
| | Test Reports | 15,000 |
| | Process Development | 100,000 |
| | 30% Design Package | 100,000 |
| | Subcontractors | 250,000 |
| | Contingencies (20% Total) | 625,000 |
| | TOTAL PHASE III | $3,749,000 |
| | TOTAL DEVELOPMENT COSTS | $4,294,000 |

TABLE E-33. SINGLE SITE TOTAL OPERATING COST - PROPORTIONAL ROTARY KILN (100 LB/HR)

| Period | Labor Cost/Year | Other Direct Cost/Yr | Duration, Yr | Total Cost |
|---|---|---|---|---|
| Eq Acceptance | 400,000 | 102,190 | 0.50 | 251,095 |
| Training & Sys | 1,200,000 | 153,280 | 0.50 | 676,640 |
| A | 1,200,000 | 306,570 | 2.43 | 3,660,970 |
| Change Out | 1,200,000 | 40,650 | 0.17 | 244,650 |
| B/C | 1,200,000 | 306,570 | 3.25 | 4,896,350 |
| Change Out | 1,200,000 | 40,650 | 0.17 | 244,650 |
| D | 1,200,000 | 306,570 | 0.90 | 1,355,910 |
| Shutdown | 400,000 | 102,190 | 0.50 | 251,095 |
| Total Life Operating Cost | | | 8.42 | $11,581,360 |

TABLE E-34. SINGLE SITE TOTAL OPERATING COST - PROPORTIONAL ROTARY KILN (400 LB/HR)

| Period | Labor Cost/Year | Other Direct Cost/Yr | Duration, Yr | Total Cost |
|---|---|---|---|---|
| Eq Acceptance | 500,000 | 178,290 | 0.50 | 339,145 |
| Training & Sys | 1,500,000 | 267,430 | 0.50 | 883,715 |
| A | 1,500,000 | 534,860 | 0.61 | 1,241,260 |
| Change Out | 1,500,000 | 55,800 | 0.17 | 310,800 |
| B/C | 1,500,000 | 534,860 | 0.81 | 1,648,240 |
| Change Out | 1,500,000 | 60,310 | 0.17 | 315,310 |
| D | 1,500,000 | 534,860 | 0.25 | 508,720 |
| Shutdown | 500,000 | 178,290 | 0.50 | 339,145 |
| Total Life Operating Cost | | | 3.51 | $5,586,335 |

TABLE E-35. SINGLE SITE TOTAL OPERATING COST - PROPORTIONAL ROTARY KILN (1000 LB/HR)

| Period | Labor Cost/Year | Other Direct Cost/Yr | Duration, Yr | Total Cost |
|---|---|---|---|---|
| Eq Acceptance | 600,000 | 299,300 | 0.50 | 449,650 |
| Training & Sys | 1,800,000 | 448,940 | 0.50 | 1,124,470 |
| A | 1,800,000 | 897,890 | 0.24 | 647,490 |
| Change Out | 1,800,000 | 80,250 | 0.17 | 386,250 |
| B/C | 1,800,000 | 897,890 | 0.32 | 863,320 |
| Change Out | 1,800,000 | 80,250 | 0.17 | 386,250 |
| D | 1,800,000 | 897,890 | 0.10 | 269,790 |
| Shutdown | 600,000 | 299,300 | 0.50 | 449,650 |
| Total Life Operating Cost | | | 2.50 | $4,576,870 |

TABLE E-36. SINGLE SITE COSTS - PROPORTIONAL ROTARY KILN

| | Agent Feed Rate | | |
|---|---|---|---|
| | 100 lb/hr | 400 lb/hr | 1000 lb/hr |
| Capital | $ 1,914,810 | $ 2,882,170 | $ 4,369,190 |
| Operating | 11,581,360 | 5,586,335 | 4,576,870 |
| Development | 4,294,000 | 4,294,000 | 4,294,000 |
| Total Life | $17,790,170 | $12,762,505 | $13,240,060 |

TABLE E-37. COLLOCATED SITE TOTAL OPERATING COST - PROPORTIONAL ROTARY KILN (1000 LB/HR)

| Period | Labor Cost/Year | Other Direct Cost/Yr | Duration, Yr | Total Cost |
|---|---|---|---|---|
| Eq Acceptance | 700,000 | 304,300 | 0.50 | 502,150 |
| Training & Sys | 2,100,000 | 456,440 | 0.50 | 1,278,220 |
| A | 2,100,000 | 912,890 | 2.42 | 7,291,190 |
| Change Out | 2,100,000 | 91,650 | 0.17 | 448,650 |
| B/C | 2,100,000 | 912,890 | 3.25 | 9,791,650 |
| Change Out | 2,100,000 | 91,650 | 0.17 | 448,650 |
| D | 2,100,000 | 912,890 | 1.04 | 3,133,410 |
| Shutdown | 700,000 | 304,300 | 0.50 | 502,150 |
| Total Life Operating Cost | | | 8.55 | $23,396,310 |

TABLE E-38. COLLOCATED SITE TOTAL OPERATING COST - PROPORTIONAL ROTARY KILN (3000 LB/HR)

| Period | Labor Cost/Year | Other Direct Cost/Yr | Duration, Yr | Total Cost |
|---|---|---|---|---|
| Eq Acceptance | 900,000 | 601,740 | 0.50 | 750,870 |
| Training & Sys | 2,700,000 | 902,600 | 0.50 | 1,801,300 |
| A | 2,700,000 | 1,805,210 | 0.81 | 3,649,220 |
| Change Out | 2,700,000 | 143,400 | 0.17 | 602,400 |
| B/C | 2,700,000 | 1,805,210 | 1.08 | 4,865,630 |
| Change Out | 2,700,000 | 169,400 | 0.17 | 628,400 |
| D | 2,700,000 | 1,805,210 | 0.36 | 1,621,880 |
| Shutdown | 900,000 | 601,740 | 0.50 | 750,870 |
| Total Life Operating Cost | | | 4.09 | $14,670,570 |

TABLE E-39. COLLOCATED SITE TOTAL OPERATING COST - PROPORTIONAL ROTARY KILN (5000 LB/HR)

| Period | Labor Cost/Year | Other Direct Cost/Yr | Duration, Yr | Total Cost |
|---|---|---|---|---|
| Eq Acceptance | 1,150,000 | 889,750 | 0.50 | 1,019,875 |
| Training & Sys | 3,450,000 | 1,334,630 | 0.50 | 2,392,315 |
| A | 3,450,000 | 2,669,260 | 0.49 | 2,998,440 |
| Change Out | 3,450,000 | 200,740 | 0.17 | 787,240 |
| B/C | 3,450,000 | 2,669,260 | 0.66 | 4,038,710 |
| Change Out | 3,450,000 | 200,740 | 0.17 | 787,240 |
| D | 3,450,000 | 2,669,260 | 0.22 | 1,346,240 |
| Shutdown | 1,150,000 | 889,750 | 0.50 | 1,019,875 |
| Total Life Operating Cost | | | 3.21 | $14,389,935 |

TABLE E-40. COLLOCATED SITE COSTS - PROPORTIONAL ROTARY KILN

| | Agent Feed Rate | | |
|---|---|---|---|
| | 1000 lb/hr | 3000 lb/hr | 5000 lb/hr |
| Capital | $ 4,615,600 | $ 8,380,380 | $11,773,270 |
| Operating | 23,396,310 | 14,670,570 | 14,389,935 |
| Development | 4,294,000 | 4,294,000 | 4,294,000 |
| Total Life Cycle Cost | $32,305,910 | $27,344,950 | $30,457,205 |

FIGURE E-5

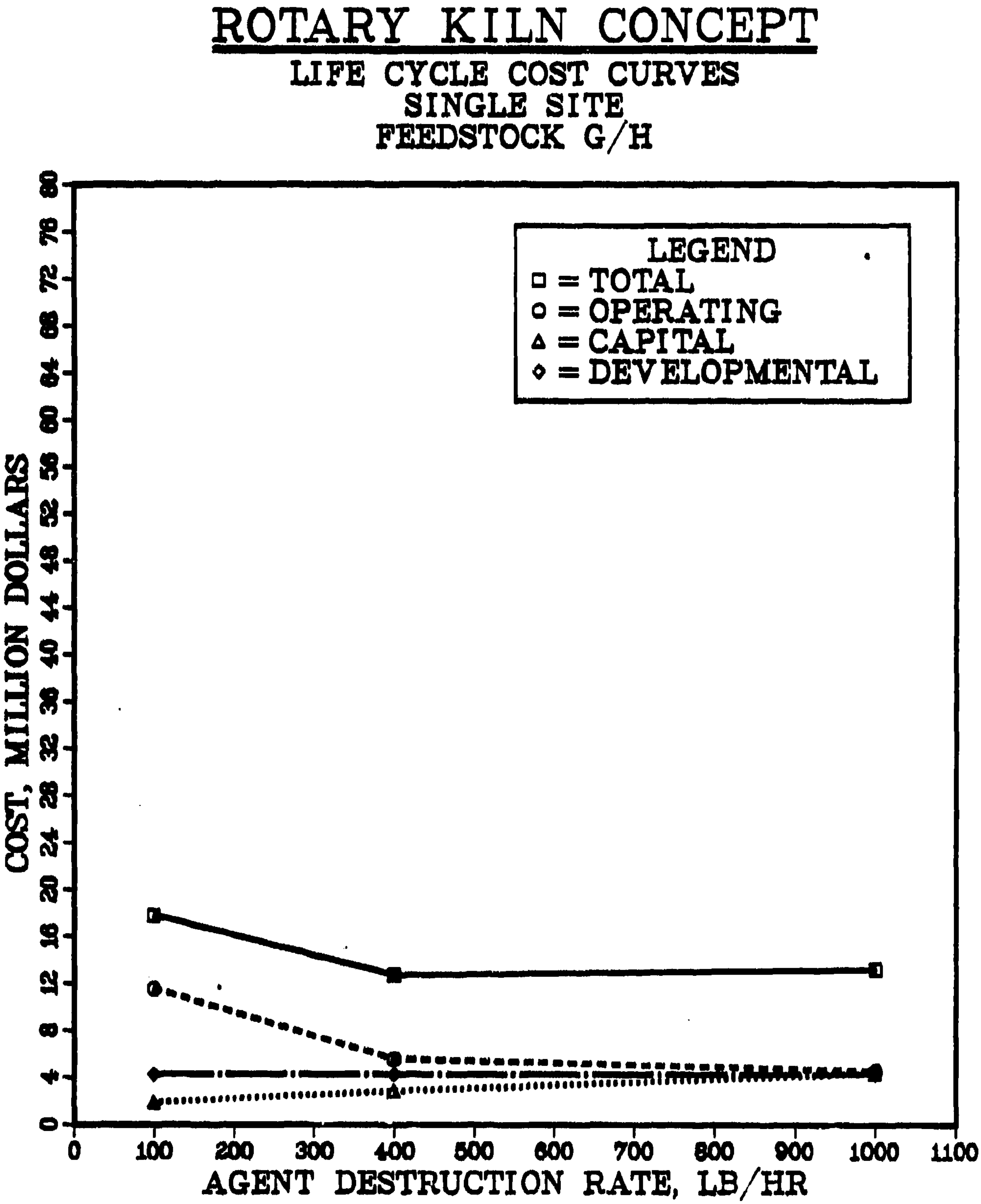
ROTARY KILN CONCEPT
LIFE CYCLE COST CURVES
SINGLE SITE
FEEDSTOCK G/H
LEGEND
□ = TOTAL
○ = OPERATING
△ = CAPITAL
◇ = DEVELOPMENTAL
COST, MILLION DOLLARS
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
72
76
80
0
100
200
300
400
500
600
700
800
900
1000
1100
AGENT DESTRUCTION RATE, LB/HR

FIGURE E-6

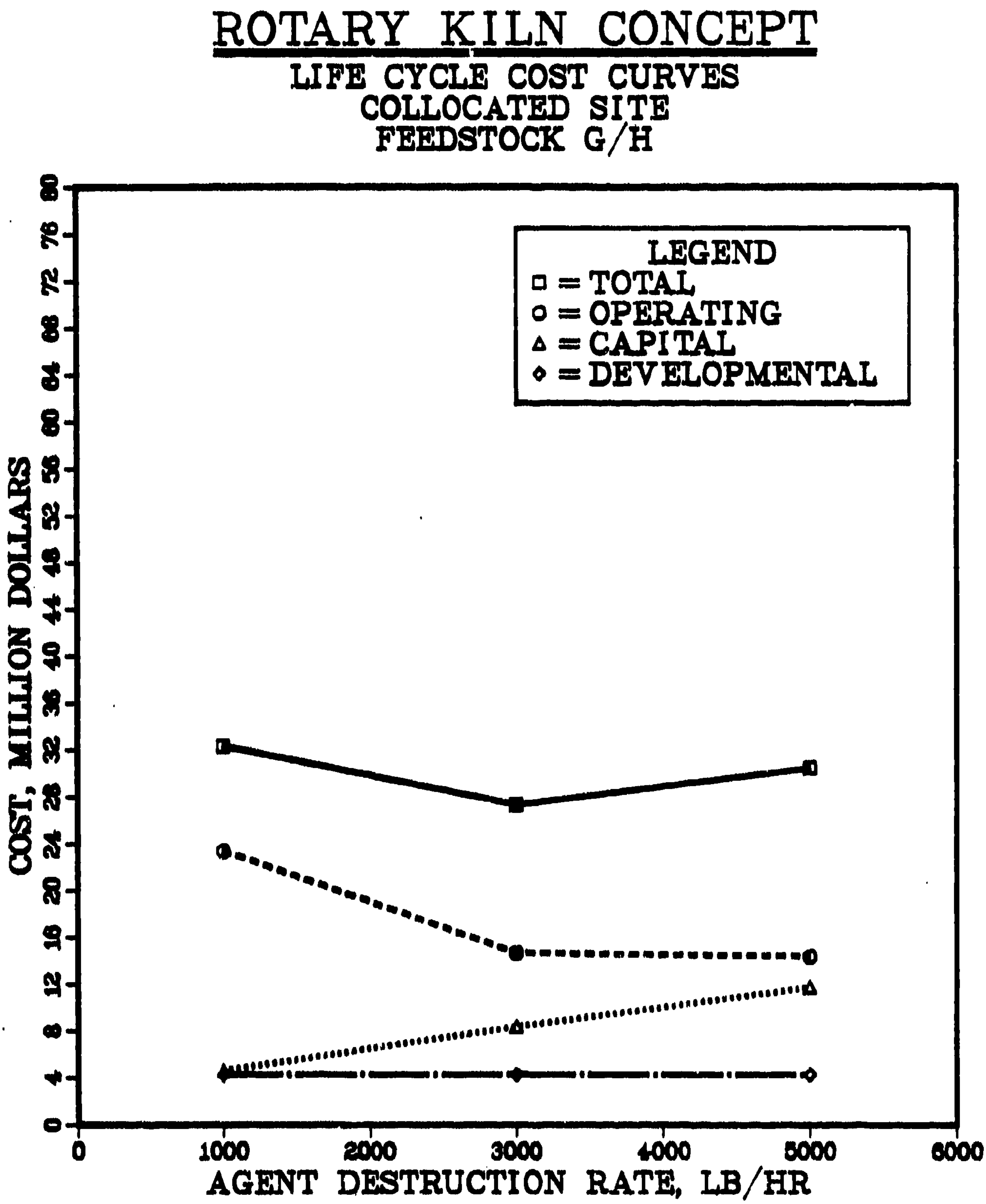
ROTARY KILN CONCEPT
LIFE CYCLE COST CURVES
COLLOCATED SITE
FEEDSTOCK G/H
LEGEND
= TOTAL
= OPERATING
= CAPITAL
= DEVELOPMENTAL
COST, MILLION DOLLARS
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
72
76
80
0
1000
2000
3000
4000
5000
6000
AGENT DESTRUCTION RATE, LB/HR

TABLE E-41. SINGLE SITE OPERATING TIME - PROPORTIONAL ROTARY KILN

| Munition Category | Munition Type | Inventory | Through-put Per Hour 100 lb/hr | Through-put Per Hour 400 lb/hr | Through-put Per Hour 1000 lb/hr | System* Availability | Production Years 100 lb/hr | Production Years 400 lb/hr | Production Years 1000 lb/hr |
|---|---|---|---|---|---|---|---|---|---|
| A | M55 Rockets | 90,000 | 9.3 | 37.4 | 93.5 | 0.881 | 1.95 | 0.49 | 0.19 |
| | M23 Mines | 20,000 | 9.5 | 38.1 | 95.2 | 0.881 | 0.48 | 0.12 | 0.05 |
| B/C | Mortars | 50,000 | 16.7 | 66.7 | 166.7 | 0.881 | 0.68 | 0.17 | 0.07 |
| | 105 mm Projectiles | 50,000 | 62.5 | 250.0 | 625.0 | 0.881 | 0.18 | 0.05 | 0.02 |
| | 155 mm Projectiles | 50,000 | 15.4 | 61.5 | 153.8 | 0.881 | 0.74 | 0.18 | 0.07 |
| | 8" Projectiles | 50,000 | 6.9 | 27.6 | 69.0 | 0.881 | 1.65 | 0.41 | 0.16 |
| D | Bombs | 800 | 0.4 | 1.8 | 4.6 | 0.881 | 0.45 | 0.10 | 0.04 |
| | Ton Containers/ Spray Tanks | 200 | 0.1 | 0.3 | 0.7 | 0.881 | 0.45 | 0.15 | 0.06 |

* Based on Thermal System only.

TABLE E-42. COLLOCATED SITE OPERATING TIME - PROPORTIONAL ROTARY KILN

| Munition Category | Munition Type | Inventory | Through-put Per Hour | | | System* | Production Years | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | 1000 lb/hr | 3000 lb/hr | 5000 lb/hr | Availability | 1000 lb/hr | 3000 lb/hr | 5000 lb/hr |
| A | M55 Rockets | 800,000 | 93.5 | 280.4 | 467.3 | 0.881 | 1.94 | 0.65 | 0.39 |
| | M23 Mines | 200,000 | 95.2 | 285.7 | 476.2 | 0.881 | 0.48 | 0.16 | 0.10 |
| B/C | Mortars | 500,000 | 166.7 | 500.0 | 833.3 | 0.881 | 0.68 | 0.23 | 0.14 |
| | 105 mm Projectiles | 500,000 | 625.0 | 1875.0 | 3125.0 | 0.881 | 0.18 | 0.06 | 0.04 |
| | 155 mm Projectiles | 500,000 | 153.8 | 465.5 | 769.2 | 0.881 | 0.74 | 0.24 | 0.15 |
| | 8" Projectiles | 500,000 | 69.0 | 206.9 | 344.8 | 0.881 | 1.65 | 0.55 | 0.33 |
| D | Bombs | 8,000 | 4.6 | 13.6 | 22.7 | 0.881 | 0.39 | 0.13 | 0.08 |
| | Ton Containers/ Spray Tanks | 2,000 | 0.7 | 2.0 | 3.3 | 0.881 | 0.65 | 0.23 | 0.14 |

* Based on Thermal System only.

APPENDIX F

# ENGINEERING AND ECONOMIC ANALYSIS - MOLTEN METAL

# APPENDIX F

## ENGINEERING AND ECONOMIC ANALYSIS - MOLTEN METAL

### Engineering Analysis

This concept takes advantage of technology commonly used in the iron and steel industry and applies it to destroy agent, agent-contaminated dunnage, and item/munition parts. Use of this state-of-the-art technology produces a simple and relatively small system capable of extremely high destruction efficiencies that has the potential to be fully automated thereby minimizing the risk and expense associated with a large operating staff. The concept is designed to process those items in the inventory which contain agent only (spray tanks, ton containers, bombs, and most of the projectiles) in feed stock configuration "c" (agent cavity opened). The remaining inventory which contains energetic materials (propellants and/or explosives) must be in configuration "e" (burster/propellant removed and the surface exposed for burning or melting). The concept also is capable of processing the entire inventory in any of feed stock configurations f, g, or h.

### A. System Concept Description

As illustrated in the conceptual drawing of the process shown in Figure F-1, the molten metal process is comprised of five integrated unit components, (1) an item/munition agent volatilization and explosive melt chamber, (2) a plasma torch agent destruction chamber, (3) a molten metal bath, (4) an afterburner, and (5) a pollution abatement system.

The first component, which interfaces with the mechanical preparation process, is the feed and volatilization chamber. This chamber consists of a tunnel, equippped with knife gate doors on

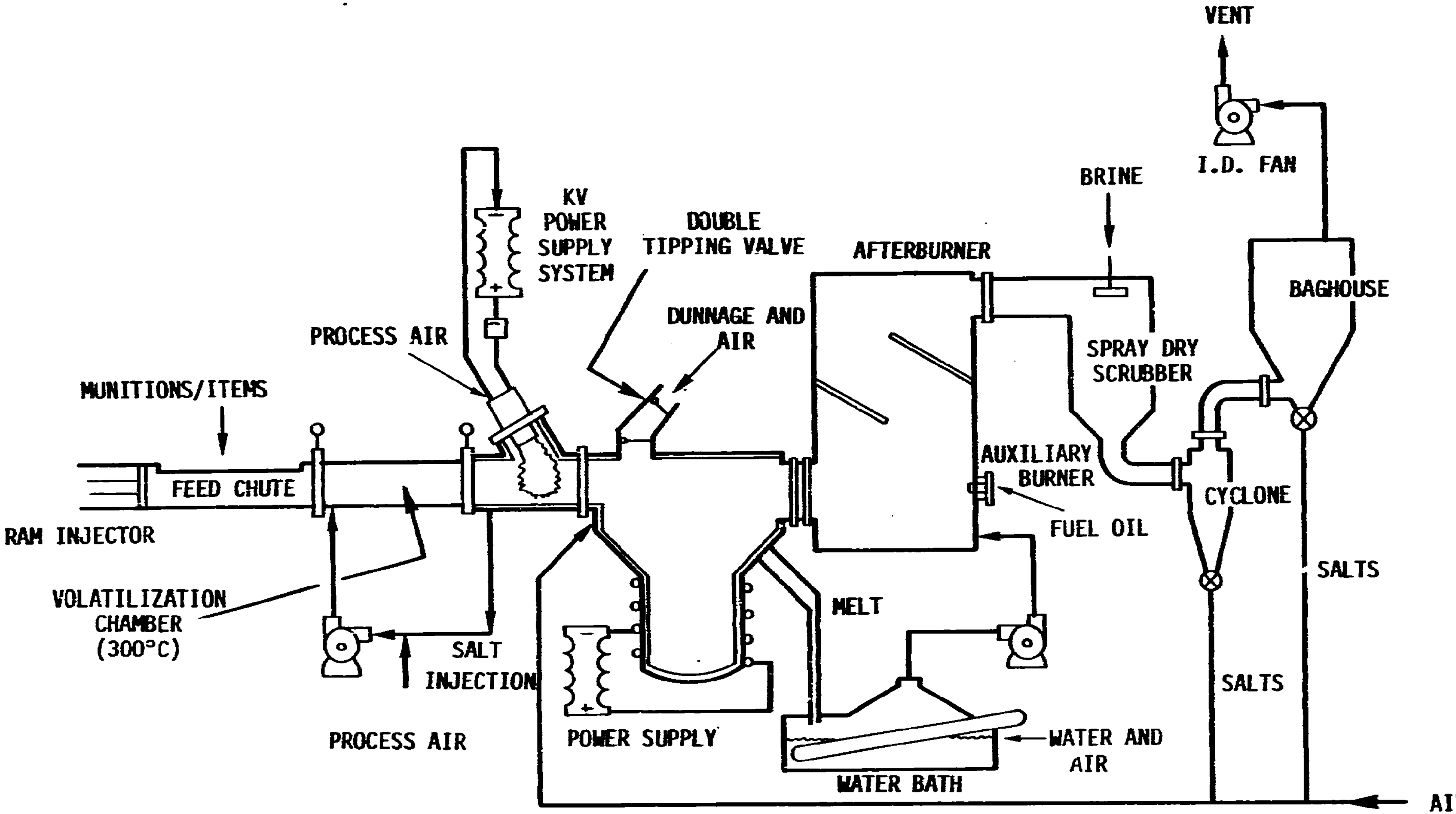


FIGURE F-1. PLASMA ARC/MOLTEN METAL

either end, and a hot gas recirculation system. It is in this chamber that controlled heating is used to volatilize the agent from the items and munitions and melt explosive from the opened burster wells.

The second unit component is the plasma chamber, consisting of an electrically powered plasma torch and a pyrolysis chamber. It is in this chamber that the volatilized agent, upon contact with the hot air stream and ionized gases of the plasma is pyrolyzed. Experimental studies with PCBs in similar systems have indicated that 99.9999 percent destruction can be achieved without producing dioxins.[1,2,3]

The third component is the molten metal reactor which consists of a molten bath comprised of steel and other metals derived from the munition bodies as well as a slag layer comprised of salt residue returned from the scrubber and silica additives. Introduction of the scruber salts into this reactor incorporates the major advantages of molten salt processing without including operability problems normally associated with that concept. The reactor serves to melt all metal item/munition components introduced into it and destroy any residual agent or organic constitutents. It also serves to destroy wood dunnage and decontaminate the scrubber salt residue to level 5X. Silica is added to the slag to vitrify the cooled salt reducing the leachability of the salt, thereby enabling it to qualify as a non-hazardous waste.

The fourth component is the afterburner that operates at 1600 F to assure that all combustible gases leaving the molten metal reactor are completely oxidized. The fifth component is the pollution abatement system which consists of a sodium hydroxide spray dry scrubber, a cyclone, and a baghouse.

Materials Flow. The flow of material through the molten metal process is represented by the process flow diagram shown in Figure F-2. The composition of the important streams, shown in Table F-1, is estimated on the assumption that 400 lb/hr of agent in stream A would be continuously accompanied by 2050 lb/hr of steel and

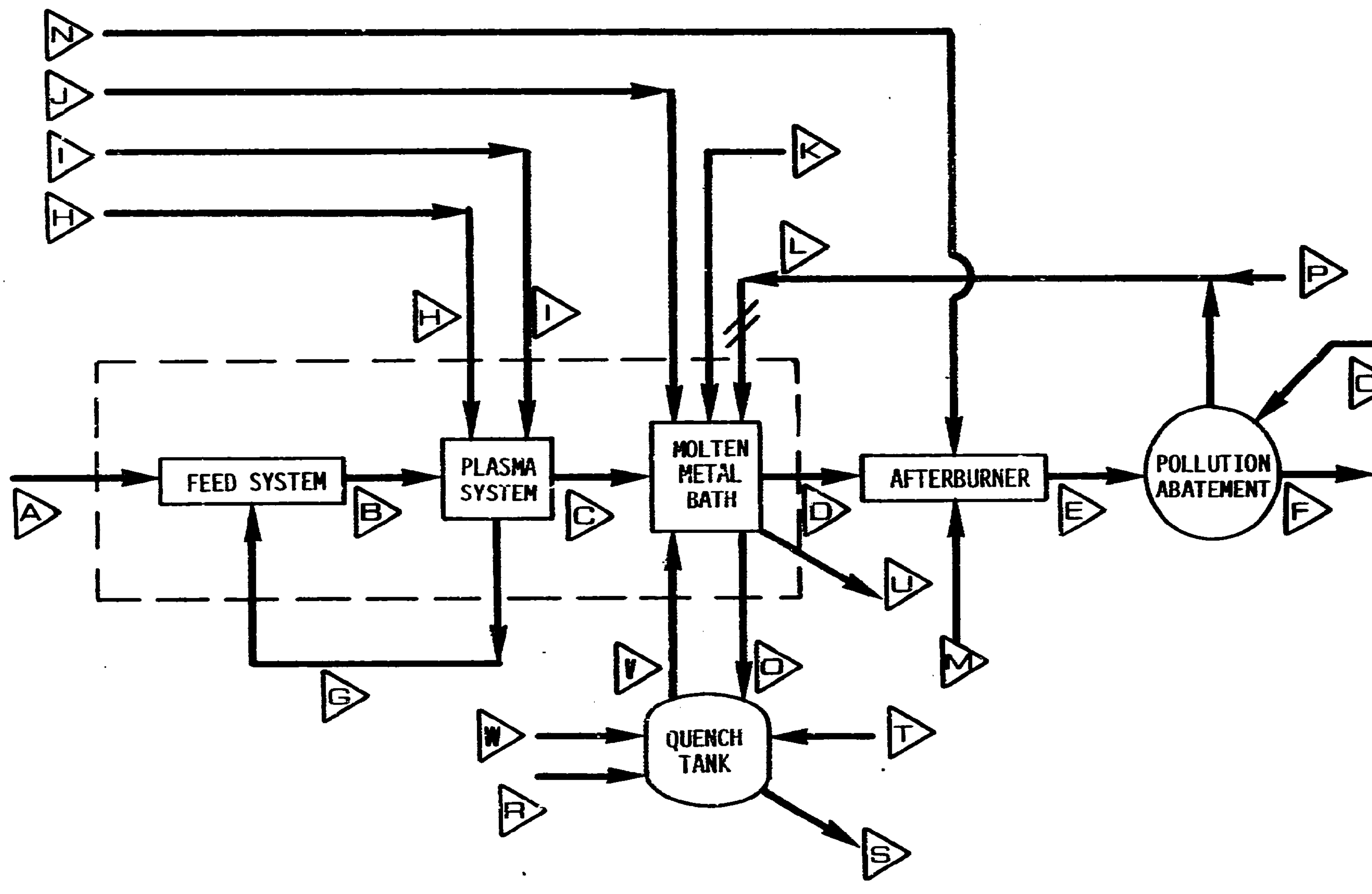


FIGURE F-2. MOLTEN METAL PROCESS FLOW DIAGRAM

TABLE F-1. ENERGY AND METAL BALANCE BASED ON 400 lb/hr of GB

| Stream | A | B | C | D | E | F | G | H | I | J |
|---|---|---|---|---|---|---|---|---|---|---|
| **Operation Conditions** | | | | | | | | | | |
| Temperature (F) | 70 | 572 | 1700 | 2500 | 1800 | 400 | 2500 | | 70 | 70 |
| Pressure (Psia) | 14.7 | 14.6 | 14.6 | 14.6 | 14.6 | 14.7 | 14.6 | | 20 | 20 |
| **Electric Energy ($10^6$ Btu)** | | | | | | | | 2.0 | | |
| Agent | 400 | 400 | | | | | | | | |
| Explosive | 250 | 250 | | | | | | | | |
| Metal Parts | 2050 | 2050 | 2050 | | | | | | | |
| Dunnage | | | | | | | | | | |
| Water | | | | | | | | | | |
| Air | | | | | | | | | 146 | 10,915 |
| Fuel Oil | | | | | | | | | | |
| Salts | | | | | | | | | | |
| **Flue Gases** | | | | | | | | | | |
| $CO_2$ | | | | 2028 | 2244 | 1995 | | | | |
| $O_2$ | | | | 1354 | 3080 | 3082 | | | 34 | 2587 |
| $N_2$ | | | | 9856 | 16,290 | 16,290 | | | 112 | 8326 |
| $H_2O$ (vapor) | | | | 1404 | 1485 | 9198 | | | | |
| HF | | | | 57 | 57 | | | | | |
| $P_2O_5$ | | | | 202 | 202 | | | | | |
| Pyrolysis Gases | | | 1229 | | | | | | | |
| **Total Mass** | 2700 | 3133 | 3273 | 14,901 | 23,358 | 30,565 | 433 | | 146 | 10,915 |
| **Elemental Distribution** | | | | | | | | | | |
| Iron | 2050 | 2050 | 2050 | | | | | | | |
| Carbon | 229 | 247 | 247 | 553 | 612 | 544 | 17.8 | | | |
| Hydrogen | 35 | 40 | 40 | 159 | 168 | 1022 | 5.1 | | | |
| Oxygen | 197 | 284 | 318 | 4191 | 6146 | 12,709 | 86.9 | | 34 | 2589 |
| Nitrogen | 46 | 364 | 476 | 9856 | 16,290 | 16,290 | 31.8 | | 112 | 8326 |
| Flourine | 54 | 56 | 54 | 54 | 54 | | 1.9 | | | |
| Phosphor | 88 | 91 | 88 | 88 | 88 | | 3.1 | | | |
| Sodium | | | | | | | | | | |

TABLE F-1. (Continued)

| Stream | K | L | M | N | O | P | Q | R | S | T | U | V | W | X |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Operation Conditions | | | | | | | | | | | | | | |
| Temperature (F) | 70 | 400 | 70 | 200 | 2800 | 70 | 70 | 50 | 200 | | 2800 | 200 | 70 | 400 |
| Pressure (Psia) | 14.7 | 20 | 20 | 14.6 | 14.6 | 20 | 20 | 45 | 14.7 | | 14.7 | 14.6 | 14.7 | 14.6 |
| Electric Energy ($10^6$ Btu) | | | | | | | | | | 1.03 | | | | |
| Agent | | | | | | | | | | | | | | |
| Explosive | | | | | | | | | | | | | | |
| Metal Parts | | | | | 2050 | | | | 2050 | | | | | |
| Dunnage | 650 | | | | | | | | | | | | | |
| Water | | | | | | | 7483 | 731 | | | | | | |
| Air | | | | | | 270 | | | | | | | 1112 | |
| Fuel Oil | | | 68 | | | | | | | | | | | |
| Salts | | | | | | | 912 | | | | 916 | | | 916 |
| Flue Gases | | | | | | | | | | | | | | |
| $CO_2$ | | | | | | | | | | | | | | |
| $O_2$ | | | | 1955 | | 64 | | | | | | | 848 | |
| $N_2$ | | | | 6434 | | 206 | | | | | | | 264 | |
| $H_2O$ (vapor) | | | | | | | | | | | | | | |
| HF | | | | | | | | | | | | | | |
| $P_2O_5$ | | | | | | | | | | | | | | |
| Pyrolysis Gases | | | | | | | | | | | | | | |
| Total Mass | 650 | 1186 | 68 | 8389 | 2050 | 270 | 8395 | 731 | 2050 | | 1188 | 1843 | 1112 | 1188 |
| Elemental Distribution | | | | | | | | | | | | | | |
| Iron | | | | | 2050 | | | | 2050 | | | | | |
| Carbon | 306 | 68 | 59.3 | | | | | | | | 68 | | | 68 |
| Hydrogen | 38 | | 18.6 | | | | 854 | 81 | | | | 81 | | |
| Oxygen | 306 | 246 | | 1955 | | 64 | 7017 | 650 | | | 454 | 914 | 264 | 454 |
| Nitrogen | | 206 | | 6434 | | 206 | | | | | | 848 | 848 | |
| Flourine | | 54 | | | | | | | | | 54 | | | 54 |
| Phosphor | | 88 | | | | | | | | | 88 | | | 88 |
| Sodium | | 524 | | | | | 524 | | | | 524 | | | 529 |

250 lb/hr of TNT in that stream and 650 lb/hr of wood in stream K. In reality, the items or munition bodies that contain agent and, if appropriate, the separated explosives placed in a melt collection tray, are alternately fed to the volatilization chamber as separate items. The heat in stream G is utilized to melt the explosives and/or volatilize the agent. For the sake of simplicity, it is assumed that the explosive did not burn until reaching the molten metal reactor. Stream B, which contains the combination of stream G and A, is swept from the volatilization chamber into the plasma chamber where the volatilized agent gases are intimately mixed with the plasma heated gas stream producing a resultant mixed gas temperature at or above 1700 F. This temperature combined with the intense mixing and ionized gases produced by the plasma, pyrolyze the agent producing stream C which consists mainly of carbon, carbon monoxide, hydrogen, nitrogen and various byproducts peculiar to the agent being processed. While the information available at this time makes determining the composition of this stream difficult, the theoretically predicted composition of this gas stream is shown in Table F-2. This pyrolysis stream and the explosives then enter the molten metal reactor where they are joined by the wood dunnage and sufficient air to burn the combustibles. The combustion products interact with the slag layer and the item/munition bodies and the melt collection trays fall into the bath where they are melted and any residual agent or explosives are volatilized and combusted. This aspect of the concept effectively eliminates any problems with polymerized mustard. Molten metal and slag are continuously removed from this system for ultimate disposal. The vitrified slag and, when processing rockets, any molten aluminum exit via stream U and are cast into drums. The other molten metals exit via stream O which take it to a water quench where it solidifies and is removed to a scrap truck by a drag conveyor. The vapor from water evaporated to cool the metal (stream R) and an equal volume of air (stream Q) are removed from the gas above the quench tank by a hood and blown back into the molten metal reactor. This helps to reduce the reactor gas temperature and restricts the gaseous effluents from the process to a single stream.

TABLE-2. PREDICTED GB
PYROLYSIS STREAM COMPOSITION

| Compound | Weight Percent |
|---|---|
| HF | 5.7 |
| $PF_3$ | 0.6 |
| $PH_3$ | 0.05 |
| HCP | 0.6 |
| $P_2$ | 2.3 |
| $P_4$ | 2.4 |
| $H_2O$ | 1.1 |
| $CO_2$ | 0.3 |
| CO | 25.3 |
| $H_2$ | 30.3 |
| $N_2$ | 31.3 |
| Other | 0.05 |
| | 100 |

The gases from the molten metal reactor (stream D) are drawn into the afterburner, to insure complete oxidation of pyrolysis products and total agent destruction. This unit also insures safe operation by providing redundancy in agent destruction capability. This burner operates on a small quantity of fuel oil (stream M) estimated at 10 percent of the total system heat input. A quantity of excess air (stream N) serves to keep the operating temperature down to 1800 F.

The afterburner flue gases then enter the pollution abatement system where remaining acid gases are removed by sodium hydroxide (stream Q) in a spray dry scrubber. Salts and other particulates are removed by a combination cyclone and baghouse and conveyed by air (stream P) to the molten metal reactor. The clean flue gases then pass through an induced draft fan that maintains the entire system at negative pressures before discharging to the atmosphere via a stack. A more detailed description of the hardware in each of these five systems including sizes and capacities for 400 lbs of agent throughput are given below.

Hardware Description.

Plasma System. The plasma system is a state-of-the-art system commercially available by Westinghouse Electric Corporation and consists of the following three subsystems;

- Plasma Torch
- Power Supply
- Controls and Instrumentation.

The plasma torch consists of a closely-spaced pair of tubuler, water cooled, copper electrodes which are spaced approximately 1 mm apart.

During operation, process air is passed through this gap and, when 4 kV or more of electric power is applied across the gap, an arc discharge is formed and immediately blown into an arc chamber where it is rotated at speeds of up to 3000 revolution per second by interaction of the arc current (up to 2000 amp) with a dc magnetic field set up by internally mounted selenoid coils. This unit is self-starting when energized and self-stabilizing during operation, eliminating spurious arc extinctions. Cooling water serves to remove excess heat from the gun to protect the electrode and prolong electrode life. Maintenance of the torch is generally restricted to electrode change after 2 weeks of operation.

Power supply characteristics must be closely matched to those of the plasma torch for optimum performance in an industrial environment. It must produce a voltage of at least 4 kV to provide spark over in the interelectrode gap in order to assure process continuity, but still handle the high negative impedance (i.e., arc voltage decreases with increasing arc current) associated with plasma. To permit the rapid heating of the hydrocarbon stream, an ac power supply is prefered. At 400 lbs/hr of agent, this supply must be capable of providing 1.5 megawatts of electrical power. State-of-the-art technology utilizes air core inductors for impendance with shunt capacitors for power correction minimizing the large power losses commonly associated with past use of plasma system and producing an overall electrical efficiency of 80 percent.

The control instrumentation consists of a console that provides the hardware to, not only control the capacitor and power transformer settings and the flows of cooling water and process air, but also to provide data acquisition and system performance monitoring. The power supply is interlocked to assures proper start-up and shut-down sequencing as well as to provide system protection in the event of equipment failure. In industrial applications, this control system is typically operated by computer.

Molten Metal System. The molten metal reactor is an adaptation of the Pyromagnetics SMT system. This system consists of a reactor and a control system and has been shown to be 80 percent energy efficient when processing municipal sludges. The reactor consists of three sections, a gas reaction zone, a transition zone, and a molten metal zone. The gases enter the cylindrical gas reactor zone radially, are mixed with air, wood, dunnage, and salt. The pyrolysis products and the dunnage burn, but the combust ion products are allowed to interact with the molten salt layer. The volume of this zone is sufficient to allow a 1 second gas residince time at 2500 F. However, its minimum dimensions are also controlled by the need to allow ton containers (30 inches high) and spray tanks (15 feet long) to fall into the molten metal zone. Consequently, the 100 and 400 lb/hr reactors have the same gas reaction zone dimensions. This zone is lined with refractory capable of resisting attack by acid gases at the extremely high operating temperatures.

Besides providing a transition from the 16 foot diameter gas reaction zone to the 8 foot diameter molten metal zone, the transition zone also contains the slag layer. To minimize the attack by molten slag, Pyromagnetics Corporation lines by a patented process. The scrubber salts, aluminum, and ash from other components are completely outgased and melted in this zone by contact with the hot gases above and the molten iron below. The agitation provided to this layer by impingement of combustion air and by falling metal parts should provide a highly active slag layer capable of removing some acid gases from the process stream and vitritying the scrubber salts.

In the molten metal zone, metal parts are melted by electrical induction heating. The induction heater is sized by the quantity of metal being melted. Besides being considered the most efficient method of heating metal parts to these temperatures, induction heating provides a significant stirring action in the melt that provides a uniform temperature avoiding hot spots and assures complete outgassing of all metal prior to removal. Induction heating does limit the vessel diameter to one capable of processing 7.5 tons/hour

of iron. However, this is only a factor at 5000 lbs/hour of agent processing rate and can be handled by simply inlcuding two metal baths connected to the transition zone.

The scrap removal system consists of a 1500 gallon water tank and a 25 foot long drag conveyor. The tank is completely enclosed by a hood which is equipped with an exhaust fan. A water system provides make-up water to the quench tank to replace the evaporative losses.

Afterburner. The afterburner system is a conventional shaft furnace and is included only to provide additional residence time at 1800 F for the flue gases from the molten metal reactor. While inclusion of this system in the process provides redundancy in agent destruction potential and provides an additional safety margin, if tests prove complete destruction of agent in the plasma, elimination of the afterburner from the design could be entertained. The air and fuel oil needed are supplied to this system through a conventional fuel oil burner.

Air Pollution Control System. Air pollution control is provided by a spray dry scrubber system which is baseline technology. This system also provides an induced draft fan. This fan is sized to be capable of removing the of flue gas produced by processing agent while maintaining a negative pressure of 5 inches of water in the feed system.

## B. System Feed Requirements

This concept is designed for feedstock configuration c/e. That is, for items which contain only agent, disassembly only to feed stock configuration c (agent cavities opened) is required. However, due to the uncertainties and technical risks associated with melting explosives from fuzed items, the inventory which contains explosives must be further disassembled to essentially configuration e (whole munition with fuze removed and buster cavity opened). It is assumed

that this operation not only will expose sufficient explosive surface area to prevent detonations but will also render rockets and mortors non-propulsive. The concept is also capable of processing feedstocks in configurations f, g, and h. In addition, since the concept requires sources of high electrical energy, it is highly compatible with advanced devices such as plasma cutting torches that might be considered for mechanical prepartion. However, not enough is known about this type of device to recommend its inclusion in the thermal process design.

## C. Pollution Abatement System

The flue gas from the afterburner is the only process stream that requires pollution abatement equipment. As stated previously, this equipment will consist of a spray dry scrubber, a baghouse, an induced draft fan, and a stack. While this is baseline technology, the Army has projected a development effort for this scrubber. If the spray dry scrubber should prove to be lacking in efficiency, this concept could be modified to incorporate a wet scrubber. By then injecting the scrubber brine into the hot gases in the molten metal reactor, the penalty of a liquid waste stream could be avoided. While it is anticipated that the molten salt layer will remove a quantity of acid gases in situ and reduce the duty on the pollution abatement system, no credit has been claimed.

## D. Ultimate Disposal

The nongaseous process effluents from this concept requiring ultimate disposal are the slag and the solidified metal scrap. Due to the nature of the concept, these materials are rendered more innocuous than the effluents from any other concept considered. The molten metal bath has the potential of converting the munition bodies into scrap that is not only 5X decontaminated but also of high quality and in a form that can be easily handled. While no reuse credit has been claimed for this scrap, its market value should be appreciable.

By reinjecting the scrubber salts into the process and melting them in the presence of scrap, the concept produces significant reductions in the ultimate disposal problem. If the salts are vitritied, they can meet RCRA requirements for non-hazardous land fills. Even if they do not, fuzed salts are estimated to have approximately twice the density of dry scrubber salts and therefore only would require half the storage or hazardous land fill volume. Another advantage is the certainty that no agent can be contained in these salts. Finally, fuzed salts do not produce the dusting problems that are associated with handling of dry salts.

## E. System Concept Advantages

Aside from having the potential for extremely high agent destruction efficiences the molten metal concept has the following additional advantages:

- Comparatively low life-cycle cost
- Single line process generates a clean gaseous effluent and decontaminated salt/metal solid waste
- Solid vitrified wastes may qualify under RCRA as non-hazardous
- No liquid waste effluents
- Comparatively simple process, few moving parts
- Versatile and flexible
  - can accept a variety of feedstocks
  - has high process rate flexibility
  - potential for operation in either pyrolitic or combustion mode.

## F. Concept Disadvantages

The potential disadvantages of this concept are:

(1) High use of electric energy for operation of the plasma gun

(2) Short opeating life of the refractory in the molten metal bath and the potential difficulty in securing compatible materials.

While the electrical energy usage of the concept is high, the overall energy consumption compares favorably with the baseline. The projected efficiencies of the plasma torch (80 percent) and the induction heater (75 percent) are quite high and, due to the high operating temperatures in these units, the fuel requirements for the afterburner will be minimal.

The short operating life of the refractory in the slag layer zone of the molten metal reactor has been incorporated in the cost analysis. Pyromagnetics estimates that with the materials presently in use, repair/replacement will be required every 3 months. While use of new materials could improve the refractory operating life, these materials require testing.

## G. System Knowledge Gaps

Though the concept is based on state-of-the-art technology and its components have been proven effective in the incineration of PCBs and municipal sludges, the incorporation of the components into one process to destroy the lethal agent inventory is novel. As such, its feasibility for lethal agent destruction must be demonstrated and the component operating characteristics better understood in order to improve the operating costs and efficiencies. The knowledge gaps associated with this concept are listed below.

High Temperature Pyrolysis of Agents. Operation of the plazma in a pyrolysis mode, while not a necessity of this concept, offers the potential to reduce the flue gas volume, improve the insitu flue gas cleanup, and eliminate the need for an afterburner. However, the high temperature pyrolysis of agents is not well defined and requires additional study to better predict the pyrolysis products.

Slag Chemistry. The chemistry of the molten slag layer is not well understood and needs further study. On the plus side, the slag has the capability of producing insitu flue gas cleanup as well as reducing the salt volume. It also offers the potential to vitrify the salts elimination hazardous materials designations. On the negative side, the slag could worsen the refractory problems in the reactor.

Energy Utilization. In the analysis of the concept, it was assumed that no interactions occurred between components and the energy requirements were the sum of those required by each component individually. In an integrated system, this would not be the case. A better determination of the energy consumptions is required.

Feed System Efficiency. The feed and volitalization system concept must be demonstrated to be efficient and trouble free. Poor heat transfer would result in materials flow problems and may require multiple feed chambers increasing both equipment and labor costs significantly.

## H. Safety

Component Safety. Incorporation of state-of-the-art technology makes this an inherently safe concept. The plasma control system is completely interlocked preventing the improper sequence of equipment operation. Such interlocking also prevents personnel access to high voltage equipment while it is energized. Standard foundry safety measures, including a metal sump pit in case of a spill, are included with the molten metal reactor. The rest of the system is also state-of-the-art technology. In short, no heroic safety measures are required.

Agent Release. The entire system operates under negative pressure which prevents leakage of agent from the process to the

environment except through the stack. Incorporation of redundant thermal systems provide backup destruction capability in the event of a component failure. In addition, the high thermal mass of the molten metal provides destruction capability even if simultaneous failure of all three thermal destruction component should occur. The potential for agent release has therefore been effectively minimized.

## I. Likelihood of Development Within 5 Years.

Again, one of the key advantages of this concept is use of proven commercially available components. Only proof of principal and refinement of the integrated system is required. Accordingly, the required development program should not exceed 5 years duration.

## J. Scalability to 400-3000 lbs/hr of Agent

Accurate scaling of the concept hardware should not be a problem. Plasma systems with power requirements far in excess of those required in this concept exists and are presently utilized in steel making operations.(5) Further, plasma pyrolysis of hydrocarbons has been performed by Westinghouse at mass flow rates up to 3600 lbs/hrs.(6)

Pyromagnetics has designed molten metal reactors capable of melting up to 15,000 lbs/hr of metal. Use of two interconnected baths will permit operation at even 25,625 lbs/hr of steel (5000 pounds of agent/hour).

## K. Degree of Technical Risk

The knowledge gaps discussed previously are associated mainly with the integration of the components into an operating system and with the projected refinements of the concept. Since the components use state-of-the-art technology and worst case assumptions were used for the evaluations, the degree of technical risks are minor

and should impact on the process operating costs, not the ability to destroy agent.

L. RAM Factors

Reliability and maintainability calculations are included in this report as a separate discussion in Appendix L. The system availability projected by these calculations is 86.2 percent of the operating time. However, this availability does not include scheduled down time for the repair of the refractory lining in the molten metal reactor. This time is included in the cost analysis and, based on vendors estimates, is assumed to require 5 to 6 days, depending on the reator size, every 3 months.

M. Material Compatability Problems

Due to the flourine content, incineration of GB is anticipated to provide materials compatability problems in any thermal process. In general this problem can be reduced by the use of high alumina refractories. However, such refractories are expensive and may not be compatible with the acid gases produced by other agents. While this problem may be expected to occur throughout this concept and will require testing, it is also inherent in the base line and is not considered a disadvantage. The incorporation of fluorine, phosphorous, chlorine, and/or sulfur in the slag layer is expected to be a more difficult problem. Pyromagnetics has refractory experience, including proprietary formulation, with the use of slags containing calcium flouirde. This experience was incorporated in the estimated refractory life already addressed earlier.

N. Energy Requirements and Source

As stated earlier, one of the disadvantages of the concept is the heavy reliance on expensive electric energy. For example, at

400 lbs/hr of agent, 3 x $10^6$ kilowatt hours/year is required by the plasma system and 2.3 x $10^6$ kilowatt hours/year is required by the molten metal system. However, this is compensated for in part by only a minimal use of fuel oil. The cverall energy costs are not excessive.

O. Ease of Operation

This single line process can either be controlled by a single operator in the control room, or fully automated for computer control. The plasma system is highly flexible and capable of processing a variety of feedstocks while operating in either a pyrolysis or oxidation mode. Operating temperatures ranging from 500 F to 4000 F are feasible with rapid response to changes in operating condition. Due to the use of electric energy, the process remains simple to control.

## Economic Analysis

To permit the development of cost optimization curves, an economic analysis of the costs to destroy a single site inventory were developed for three processing rates, 100, 400, and 1000 lbs/hr of agent as well as the costs to destroy the collocated inventory of processing rates of 400, 1000, 3000, and 5000 lbs of agent/hour. In developing these costs, Army guidelines were followed when appropriate and any exceptions have been noted. Since most of the hardware required by this concept is commercially available, the preferred source of information on purchase costs, installation costs, and operating costs, as well as the space requirements of the components was the estimates supplied by the vendors. The baseline was also used as an information source for hardware, such as spray dry scrubbers, that have usage in common with the baseline. When these types of information were not available, Guthrie,[7] Peters and Timmerhaus[8] or other appropriate engineering literature was used. These same

information sources were also consulted for exponential scaling factors. When none were available, a 0.6 factor was used. The estimates developed are presented below organized by category.

## A. Facility Costs

In estimating the facility costs Army cost guidelines were followed and general facilities requirements such as utilities, security, laboratories, and site improvements were assumed to be part of the mechanical preparation. It was assumed that all areas upstream of the afterburner were agent containment areas and, for the rest of the thermal process equipment, only nonagent floor space was required. Since a nondetonable feedstock has been specified, no explosive containment was required. When appropriate, equipment has been placed outside on pads reducing the facility cost. Since this concept requires usages of electricity and cooling water that might not be anticipated in mechanical preparation area design, extra pad space was allowed for including these utilities. Pad space was also provided for spent salt storage even though it is probable that it will not be required for this concept. Due to the size requirements of the ton container and spray tanks, the minimum reactor area was determined to be 2900 $ft^2$ (400 lb/hr of agent). The facility costs developed for single site operations can be found in Table F-3 and those for collocated site operations can be found in Table F-4.

## B. Capital Equipment Costs

Purchase costs of the thermal plasma hardware, the molten metal reactor, the cooling tower, and the afterburner for all five capacities were supplied by the appropriate vendors. The installation costs were assumed to add 40 percent to the purchase costs. The metal quench tank and drag conveyor were estimated from engineering literature[7] based on a 1500 gallon tank and a 98 inch wide, 25 foot

TABLE F-3. FACILITY COSTS - SINGLE SITE

| Item | Agent Destruction Rate 100 lb/hr | 400 lb/hr | 1000 lb/hr |
|---|---|---|---|
| Reactor (Agent Area)[(a)] | 2900 $ft^2$ | 2900 $ft^2$ | 4600 $ft^2$ |
| at $400/$ft^2$ | $ 1,160,000 | $ 1,160,000 | $ 1,840,000 |
| Afterburner Area[(b)] | 310 $ft^2$ | 630 $ft^2$ | 1100 $ft^2$ |
| at $90/$ft^2$ | $ 27,900 | $ 56,700 | $ 99,000 |
| Metal Quench Area[(b)] | 375 $ft^2$ | 375 $ft^2$ | 500 $ft^2$ |
| at $90/$ft^2$ | $ 33,250 | $ 33,750 | $ 45,000 |
| Pads | | | |
| Cooling water[(a)] | 500 $ft^2$ | 750 $ft^2$ | 1200 $ft^2$ |
| Scrap handling | 2500 $ft^2$ | 2500 $ft^2$ | 2500 $ft^2$ |
| Salt Storage[(c)] | 1000 $ft^2$ | 2500 $ft^2$ | 4300 $ft^2$ |
| Electrical yard[(a)] | 1150 $ft^2$ | 2600 $ft^2$ | 4500 $ft^2$ |
| Fuel Tanks[(c)] | 330 $ft^2$ | 660 $ft^2$ | 1320 $ft^2$ |
| Total Pad Area | 5480 $ft^2$ | 9010 $ft^2$ | 13820 $ft^2$ |
| Pad Costs at $2.5/$ft^2$ | $ 13,700 | $ 22,525 | $ 34,550 |
| Total Facility Costs | $ 1,235,000 | $ 1,273,000 | $ 2,019,000 |

(a) Vendor supplied.
(b) Guthrie.
(c) Scaled from baseline.

TABLE F-4. COLLOCATED FACILITY COSTS

| Item | Agent Destruction Rate 400 lb/hr | 1000 lb/hr | 3000 lb/hr | 5000 lb/hr |
|---|---|---|---|---|
| Reactor (Agent Area) | 2900 $ft^2$ | 4600 $ft^2$ | 7800 $ft^2$ | 10,000 $ft^2$ |
| at 900/$ft^2$ (a) | $1,160,000 | $1,840,000 | $3,120,000 | $4,000,000 |
| Afterburner Area (b) | 630 $ft^2$ | 1100 $ft^2$ | 2752 $ft^2$ | 3952 $ft^2$ |
| at $90/$ft^2$ | $ 56,700 | $ 99,000 | $ 247,680 | $ 355,680 |
| Metal Quench Area (b) | 375 $ft^2$ | 500 $ft^2$ | 970 $ft^2$ | 1320 $ft^2$ |
| at $90/$ft^2$ | $ 33,750 | $ 45,000 | $ 87,300 | $ 118,800 |
| Pads | | | | |
| Cooling water (a) | 750 $ft^2$ | 1200 $ft^2$ | 2300 $ft^2$ | 3200 $ft^2$ |
| Scrap handling | 2500 $ft^2$ | 2500 $ft^2$ | 5000 $ft^2$ | 5000 $ft^2$ |
| Salt storage (c) | 11,300 $ft^2$ | 11,300 $ft^2$ | 11,300 $ft^2$ | 11,300 $ft^2$ |
| Electrical yard (a) | 2600 $ft^2$ | 4500 $ft^2$ | 8750 $ft^2$ | 12,000 $ft^2$ |
| Fuel tanks (c) | 660 $ft^2$ | 1320 $ft^2$ | 2640 $ft^2$ | 3960 $ft^2$ |
| Total Pad Area | 17,060 $ft^2$ | 19,620 $ft^2$ | 27,690 $ft^2$ | 32,260 $ft^2$ |
| Pad Costs at $2.5/$ft^2$ | $ 44,525 | $ 52,050 | $ 74,975 | $ 88,650 |
| Total Facility Costs | $1,295,000 | $2,036,000 | $3,530,000 | $4,563,000 |

(a) Vendor supplied.
(b) Guthrie.
(c) Scaled from baseline.

long conveyor for 1000 lb/hr of agent. Other sizes were scaled from there. The hood and exhaust fan for this unit were costed similary based on the need to remove the water being evaporated. The remaining hardware was costed from the baseline. The spray dry scrubber and bag house costs were scaled based on flue gas volume. The heat exchanger scaled from BTU's in the system. Since state-of-the-art hardware is utilized, design costs of 25 percent were assumed. The single site costs are summarized in Table F-5. The collocation costs can be found in Table F-6.

## C. Operating Costs

To estimate the life cycle operating costs it was first necessary to estimate labor costs and other operating costs on a yearly basis. The inventory volume, the processing rates, and the system availability were then used to determine the required number of production years. These numbers could then be combined to produce total life cycle operating costs.

Labor Costs. Do to the ease of operation, the majority of this system is automated. This results in very low labor requirements. The control room operating room requirements are based on information supplied by the vendor. Since molten metal bath waste stream handling is fully automated, the only labor requirement is for personnel to monitor the system and move the disposal bins and trucks when necessary. Mainteinance personnel have been added to the operating staff to monitor the equipment operations and to be available to effect repairs. It was assumed that additional skilled maintenance personnel would be available from the overall facility if needed. At higher throughput rates the major impact is on increased requirements for these maintenance personnel. Since the materials handling operation also increase in magnitude, operators were added here and an additional control room operator added to monitor the

TABLE F-5. CAPITAL EQUIPMENT COSTS SINGLE SITE - INSTALLED COSTS

| Item | Agent Destruction Rate 100 lb/hr | 400 lb/hr | 1000 lb/hr |
|---|---|---|---|
| Thermal Process Equipment | | | |
| Plasma System[a] | | | |
| Torch plus Reactor | $ 100,800 | $ 231,000 | $ 365,000 |
| Controls and Instrumentation | 105,000 | 280,000 | 329,000 |
| Electrical Source | 182,000 | 412,000 | 651,000 |
| Molten Metal System[a] | $ 225,000 | $ 595,000 | $1,120,000 |
| Metal Quench Tank and Conveyor[b] | 51,800 | 57,800 | 100,000 |
| Metal Quench Tank Exhaust Hood[b] | 2,000 | 4,600 | 8,000 |
| Feed System | 100,000 | 100,000 | 100,000 |
| Afterburner[a] | 124,000 | 285,000 | 495,000 |
| Fuel Tanks[c] | 5,000 | 9,000 | 18,000 |
| Cooling Tower[a] | 20,000 | 28,000 | 35,000 |
| Furnace Area Heat Exchanger[c] | 35,000 | 80,000 | 140,000 |
| SUBTOTAL-Thermal Process Equipment | $ 986,600 | 2,081,400 | 3,361,000 |
| Pollution Abatement Equipment[c] | | | |
| Spray Dry Scrubber | 81,000 | 177,000 | 368,000 |
| Baghouse, I.D. Fan, Stack | 203,000 | 307,000 | 578,000 |
| SUBTOTAL-Abatement Equip Costs | 284,000 | 484,000 | 946,000 |
| Ultimate Disposal | | | |
| Fork Truck[c] | 22,000 | 22,000 | 44,000 |
| Scrap Truck and Bins | 40,000 | 60,000 | 100,000 |
| SUBTOTAL-Ultimate Disposal | 62,000 | 82,000 | 144,000 |
| SUBTOTAL-Equipment Costs | 1,332,600 | 2,648,400 | 4,451,000 |
| Design Cost (25%) | 333,150 | 662,100 | 1,112,750 |
| TOTAL-Capital Equipment Costs | $1,665,750 | $3,310,500 | $5,563,750 |

(a) Vendor supplied
(b) Scaled from baseline.

TABLE F-6. CAPITAL EQUIPMENT INSTALLATION COSTS - COLLOCATED SITE

| Item | Agent Destruction Rate 400 lb/hr | 1000 lb/hr | 3000 lb/hr | 5000 lb/hr |
|---|---|---|---|---|
| THERMAL PROCESS EQUIPMENT | | | | |
| Plasma System[a] | | | | |
| Tourch and Reactor | $ 231,000 | $ 365,000 | $ 777,000 | $ 1,176,000 |
| Controls and Instrumentation | 280,000 | 329,000 | 483,000 | 728,000 |
| Electrical Source | 412,000 | 651,000 | 1,379,000 | 2,100,000 |
| Molten Metal System[a] | 595,000 | 1,120,000 | 3,010,000 | 5,110,000 |
| Metal Quench Tank and Conveyor[b] | 57,800 | 100,000 | 300,000 | 500,000 |
| Metal Tank Exhaust Hood[b] | 4,600 | 8,000 | 16,000 | 21,000 |
| Feed System | 100,000 | 100,000 | 100,000 | 100,000 |
| Afterburner | 285,000 | 445,000 | 955,000 | 1,300,000 |
| Fuel Tanks[c] | 9,000 | 18,000 | 36,000 | 54,000 |
| Cooling Tower[c] | 28,000 | 35,000 | 40,000 | 45,000 |
| Furnace Area Heat Exchanger[c] | 80,000 | 140,000 | 270,000 | 360,000 |
| SUBTOTAL | $2,081,400 | $ 3,361,000 | $ 7,365,200 | $11,194,000 |
| Pollution Abatement Equipment[c] | | | | |
| Spray Dry Scrubber | 177,000 | 368,000 | 692,000 | 937,000 |
| Baghouse and I.D. Fan | 307,000 | 578,000 | 952,000 | 1,288,000 |
| SUBTOTAL | $ 484,000 | $ 946,000 | $ 1,644,000 | $ 2,225,000 |
| Ultimate Disposal | | | | |
| Fork Truck[c] | 22,000 | 44,000 | 88,000 | 132,000 |
| Scrap Truck and Bins | 60,000 | 100,000 | 150,000 | 200,000 |
| SUBTOTAL | $ 82,000 | $ 144,000 | $ 238,000 | $ 332,000 |
| SUBTOTAL-Equipment Costs | 2,648,400 | 4,451,000 | 9,247,200 | 13,751,000 |
| Design Costs (25%) | 662,100 | 1,112,750 | 2,311,800 | 3,437,750 |
| TOTAL-Capital Costs | $3,310,500 | $ 5,563,750 | $11,559,000 | $17,188,750 |

(a) Vendor supplied estimate.
(b) Guthrie
(c) Scaled from baseline.

increased auxiliary equipment. It was assumed that supervision for the overall operation would be supplied by the overall facility. The personnel requirements are summarized in Table F-7.

Other Direct Costs.

Electricity. Of the utilities, the electricity usage is the major item. Most of the electricity usage is estimated directly from vendor-supplied information. The pollution abatement charges are scaled from the baseline. A miscellaneous electrical usage category, costed at 10 percent of the total, was included to cover miscellaneous pumps and blowers.

Water. Water usage in the spray dryer and the metal quench are based on the water required to reduce the temperature of the feed streams to 400 F and 200 F respectively. The cooling water make up requirements were assumed to be 10 percent of the cooling water circulation rates that were specified by the thermal system vendors.

Fuel Oil. Since the afterburner would be idling most of the time, it was assumed that the fuel oil need would be equivalent to 10 percent of the total BTU's being put through the system.

Spare Parts. Since few moving parts exist in this system, it was assumed that spare parts requirements less than those of other concepts would be. Therefore, 4 percent of the capital equipment costs was used and adjusted to include vendor estimate for the cost plasma electrodes.

Materials. The baseline estimate for materials of 10 percent of the "other" costs was used. This was assumed to include caustic for the spray dryer.

The other direct costs are summarized below in Tables F-8 and F-9.

TABLE F-7. SYSTEM PERSONNEL REQUIREMENTS

| | Personnel/Shift Agent Rate | | | | |
|---|---|---|---|---|---|
| | 100 | 400 | 1000 | 3000 | 5000 |
| Feed System | 1 | 1 | 1 | 2 | 2 |
| Control Room | | | | | |
| Furnace Systems | 1 | 1 | 1 | 1 | 1 |
| Utilities & Others | 1 | 1 | 1 | 1 | 2 |
| Maintenance | 2 | 2 | 3 | 3 | 4 |
| Pollution Abatement | 0.5 | 0.5 | 1 | 1.5 | 1.5 |
| Ultimate Disposal | 0.5 | 0.5 | 1 | 1.5 | 1.5 |
| TOTAL/SHIFT | 6 | 6 | 8 | 10 | 12 |
| Shifts/Day | x3 | x3 | x3 | x3 | x3 |
| Person Years/Year | 18 | 18 | 24 | 30 | 36,000 |
| Rate | x50,000 | x50,000 | x50,000 | x50,000 | x50,000 |
| LABOR COSTS/YEAR | 900,000 | 900,000 | 1,200,000 | 1,500,000 | 1,800,000 |

TABLE F-8. OTHER DIRECT COSTS - SINGLE SITE

| Item Usage Cost | Agent Feed Rate 100 lb/hr | 400 lb/hr | 1000 lb/hr |
|---|---|---|---|
| Water - $x10^6$ gal/year - \$0.53/1000 gal | | | |
| Spray Dryer[c] | 0.82 | 3.29 | 8.22 |
| Cooling Tower Makeup[b] | 3.00 | 5.85 | 8.55 |
| Metal Quench Losses[a] | 0.12 | 0.49 | 1.22 |
| SUBTOTAL | 3.94 | 9.63 | 17.99 |
| Cost/year at \$0.53/1000 gal | \$2,088 | \$5,104 | \$9,535 |
| Electric - x $10^6$ KwHr/Yr - \$0.05/kwHr | | | |
| Thermal | | | |
| Plasma[b] | 1.08 | 4.33 | 10.8 |
| Induction Furnace[b] | 0.58 | 2.30 | 5.75 |
| Cooling Tower[b] | 0.05 | 0.07 | 0.11 |
| Afterburner[c] | 0.07 | 0.16 | 0.36 |
| Vaporizer Blower | 0.01 | 0.05 | 0.12 |
| Heat Exchanger[c] | 0.05 | 0.11 | 0.19 |
| Scap Quench | 0.01 | 0.05 | 0.12 |
| SUBTOTAL Thermal System | 1.85 | 7.07 | 17.45 |
| Pollution Abatement | | | |
| Scrubber and I.D. Fan[c] | 0.22 | 0.59 | 0.85 |
| Scrap Exhaust Hood | 0.03 | 0.07 | 0.12 |
| SUBTOTAL | 0.26 | 0.63 | 0.97 |
| Miscellaneous | 0.20 | 0.7 | 1.8 |
| Total Electrical Use | 2.31 | 8.40 | 20.22 |
| Yearly Costs at \$0.05/KwH | \$115,500 | \$420,000 | \$1,011,000 |
| Fuel Oil - Gallon/Year | 11,750 | 47,000 | 117,500 |
| Cost/Year at \$1.20/Gal | \$ 14,100 | \$ 56,400 | \$ 141,100 |
| Spare Parts | 73,170 | 161,430 | 263,475 |
| Materials (10% Other Costs) | \$ 110,486 | \$ 154,293 | \$ 262,501 |
| TOTAL OTHER DIRECT COSTS \$/Yr | \$ 315,344 | \$ 797,227 | \$1,687,511 |

(a) Calculated.
(b) Vendors estimate.
(c) Scaled from baseline.

TABLE F-9. OTHER DIRECT COSTS - COLLOCATED SITE

| Item Usage Rate | Agent Feed Rate | | | |
|---|---|---|---|---|
| | 400 lb/hr | 1000 lb/hr | 3000 lb/hr | 5000 lb/hr |
| Water in $10^6$ gallon/yr - $0.53/gallon | | | | |
| Spray Dryer[a] | 3.29 | 8.22 | 24.68 | 41.13 |
| Cooling Tower Makeup[b] | 5.85 | 8.55 | 14.10 | 18.15 |
| Metal Quench Losses[a] | 0.49 | 1.22 | 3.66 | 6.10 |
| SUBTOTAL | 9.63 | 17.99 | 42.44 | 65.38 |
| COST at $0.53/gallon | $5,104 | $9,535 | $22,493 | $34,651 |
| Electricity - $10^6$ KwH/yr - $0.05/KwH | | | | |
| Thermal Systems | | | | |
| Plasma[b] | 4.33 | 10.8 | 32.5 | 54.1 |
| Induction Furnace[b] | 2.3 | 5.75 | 17.26 | 28.76 |
| Cooling Tower[b] | .07 | .11 | 0.18 | 0.25 |
| Afterburner[c] | .16 | .36 | 0.57 | 0.94 |
| Vaporizer Blower | .05 | .12 | 0.19 | 0.23 |
| Heat Exchanger[c] | 0.11 | 0.19 | 0.37 | 0.50 |
| Scrap Quench | 0.05 | 0.12 | 0.37 | 0.62 |
| SUBTOTAL | 7.07 | 17.45 | 51.44 | 85.4 |
| Pollution Abatement | | | | |
| Scrubber and I.D. Fan[c] | 0.59 | 0.85 | 1.33 | 2.70 |
| Scrap Exhaust Hood | 0.07 | 0.12 | 0.24 | 0.38 |
| SUBTOTAL | 0.63 | 0.97 | 1.57 | 3.08 |
| Miscellaneous (10%) | .70 | 1.8 | 5.25 | 8.72 |
| Total Electrical Use | 8.40 | 20.22 | 58.78 | 96.82 |
| Costs at $.05/KwH | $420,000 | $1,011,000 | $2,939,000 | $4,841,100 |
| Fuel Oil - Gallon/Year | 47,000 | 117,500 | 352,500 | 587,500 |
| Spare Parts (6% of Capital Costs) | $161,430 | $263,475 | $579,135 | $920,250 |
| Materials (10% of Other Costs) | $184,293 | $262,501 | $546,392 | $830,100 |
| TOTAL OTHER DIRECT COSTS | $827,227 | $1,687,511 | $4,510,321 | $7,331,101 |

(a) Calculated.
(b) Vendors estimate.
(c) Scaled from baseline.

## Total Operating Costs

Production Time. Summaries of the single and collocated site production time estimates for each inventory item at the various processing rates can be found in Tables F-10 and F-11. Production years for each inventory item are determined by dividing the number of items in the inventory by the product of the hourly processing rate, the 5000 hr/yr operating schedule, and the system availability determined in the RAM analysis. Each inventory category subtotal was computed using Army guidelines. Scheduled maintenance time was then determined as follows. The molten metal vendor estimates that the slag zone refractory must be repaired or replaced every 3 months or four times per year. Their experience indicates that the refactory can be replaced and cured in 3 to 6 days depending on the size of the reactor. The total scheduled maintenance time was then computed as follows. The Inventory Category subtotals were added to determine the years of operation. The total number of scheduled refractory changes was then determined by multiplying the years of operation by four. The hours of down time was computed by multiplying the number of changes by the vendors estiamte of the time required change. The years of scheduled maintenance was then determined by dividing the total hours by the 5000 hr/yr operating schedule.

Life Cycle Operating Costs. The production years per inventory category computed above were the used, following the Army guidelines, to compute the life cycle operating costs for demilitarizing the single site and collocated site inventories at each of the appropriate processing rates. The scheduled maintenance was assumed to have the same operating costs as the change over periods requiring full labor and 50 percent of the other operating cost.

TABLE F-10. THERMAL PROCESS OPERATING TIME - SINGLE SITE

| Munition Category | Munition Type | Inventory | Through-put Per Hour | | | System Availability | Production Years | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | 100 lb/hr | 400 lb/hr | 1000 lb/hr | | 100 lb/hr | 400 lb/hr | 1000 lb/hr |
| A | M-55 Rockets | 80,000 | 9.3 | 37.4 | 93.5 | 0.862 | 2.00 | 0.50 | 0.20 |
| | M-23 Mines | 20,000 | 9.5 | 38.1 | 95.2 | 0.862 | 0.49 | 0.12 | 0.05 |
| | SUBTOTAL | | | | | | 2.49 | 0.62 | 0.25 |
| B/C | Mortars | 50,000 | 16.7 | 66.7 | 166.7 | 0.862 | 0.69 | 0.17 | 0.07 |
| | 105 mm Projectiles | 50,000 | 62.5 | 250.0 | 625.0 | 0.862 | 0.19 | 0.05 | 0.02 |
| | 155 mm Projectiles | 50,000 | 15.4 | 61.5 | 153.8 | 0.862 | 0.75 | 0.19 | 0.08 |
| | 8" Projectiles | 50,000 | 6.9 | 27.6 | 69.0 | 0.862 | 1.68 | 0.42 | 0.17 |
| | SUBTOTAL | | | | | | 3.31 | 0.83 | 0.34 |
| D | Bombs | 800 | 0.4 | 1.8 | 4.6 | 0.862 | 0.46 | 0.10 | 0.04 |
| | Ton Containers/ Spray Tanks | 200 | 0.1 | 0.3 | 0.7 | 0.862 | 0.46 | 0.15 | 0.07 |
| | SUBTOTAL | | | | | | 0.92 | 0.25 | 0.11 |
| Scheduled Maintenance Refractory Changes Every 3 Months (5-6 days) | | | | | | | 0.35 | 0.11 | 0.06 |

TABLE F-11. THERMAL PROCESS OPERATING TIME - COLLOCATED SITE

| Category | Munition Type | Inventory | Throughput per Hour 400 lb/hr | Throughput per Hour 1000 lb/hr | Throughput per Hour 3000 lb/hr | Throughput per Hour 5000 lb/hr | System Availability | Production Years 400 lb/hr | Production Years 1000 lb/hr | Production Years 3000 lb/hr | Production Years 5000 lb/hr |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A | M-55 Rockets | 800,000 | 37.4 | 93.5 | 280.4 | 467.3 | 0.862 | 4.96 | 1.98 | 0.648 | 0.397 |
| | M-23 Mines | 200,000 | 38.1 | 95.2 | 285.7 | 476.2 | 0.862 | 1.22 | 0.487 | 0.162 | 0.097 |
| | SUBTOTAL | | | | | | | 6.18 | 2.47 | 0.81 | 0.49 |
| B/C | Mortars | 500,000 | 66.7 | 166.7 | 500.0 | 833.3 | 0.862 | 1.74 | 0.696 | 0.23 | 0.139 |
| | 105 mm Projectiles | 500,000 | 250.0 | 625.0 | 1875.0 | 3125.0 | 0.862 | 0.46 | 0.186 | 0.06 | 0.037 |
| | 155 mm Projectiles | 500,000 | 61.5 | 153.8 | 465.5 | 769.2 | 0.862 | 1.88 | 0.754 | 0.25 | 0.151 |
| | 8" Projectiles | 500,000 | 27.6 | 69.0 | 206.9 | 344.8 | 0.862 | 4.20 | 1.68 | 0.56 | 0.336 |
| | SUBTOTAL | | | | | | | 10.50 | 3.32 | 1.10 | 0.66 |
| D | Bombs | 8,000 | 1.8 | 4.6 | 13.6 | 22.7 | 0.862 | 1.03 | 0.40 | 0.136 | 0.082 |
| | Ton Containers/ Spray Tank | 2,000 | 0.3 | 0.7 | 2.0 | 3.3 | 0.862 | 1.55 | 0.66 | 0.23 | 0.141 |
| | SUBTOTAL | | | | | | | 2.58 | 1.06 | 0.368 | 0.22 |
| Scheduled Maintenance Refractory Changes Every 3 months (5-6 days) | | | | | | | | 1.04 | 0.548 | 0.194 | 0.123 |

Summaries of the life cycle operating costs for single sites can be found in Table F-12, F-13, and F-14. The collocated site costs are summarized in Tables F-15, F-16, F-17, and F-18.

D. Development Costs

To fully develop the concept, both bench scale and pilot scale studies are necessary. In the bench scale studies, pyrolysis of agent with a plazma arc should be deomonstrated and the products of pyrolysis identified. Additional molten metal studies are also required to determine the interaction between the slag layer and the flue gas. The aim of these studies would be to determine the feasibility of insitu clean up of the products of the plazma arc destruction step. Refractory compatability studies are also needed. After eliminating these and other knowledge gaps, a new conceptual design of the process should be completed. At this time, if the process is proven to be feasable, a 40 lb/hr pilot plant would be designed and built. A summary of the estimated development costs can be found in Table F-19. Estimates of the cost of designing, constructing, and operating the pilot plant were scaled directly from the 100 lb/hr estimates presented previously.

E. Total Costs

The total costs for each feed rate under consideration is simply the sum of the facility costs, the capital equipment costs, the life cycle operating costs, and the development costs. These costs are summarized in Tables F-20 and F-21.

F. Optimum Process Flow Rate

From an operational standpoint, the optimum flow rate for this process is probably determined by the mechanical preparation area or perhaps the feed system. The optimum flow rate from a cost

TABLE F-12. LIFE CYCLE OPERATING COSTS - SINGLE SITE
(100 LB/HR)

| Period | Rate, Labor $/Yr | Rate, Other $/Yr | Duration | Total Cost, $ |
|---|---|---|---|---|
| Eq Acceptance | $ 300,000 | $ 105,115 | 0.50 | $ 202,557 |
| Training | 900,000 | 157,672 | 0.50 | 528,836 |
| Inventory Item A | 900,000 | 315,344 | 2.49 | 3,026,207 |
| Change Out | 900,000 | 157,672 | 0.17 | 179,804 |
| Inventory Item B | 900,000 | 315,344 | 3.31 | 4,022,789 |
| Change Out | 900,000 | 157,672 | 0.17 | 179,804 |
| Inventory Item D | 900,000 | 315,344 | 0.92 | 1,118,117 |
| Scheduled Maintenance | 900,000 | 157,672 | 0.35 | 370,185 |
| Shutdown | 300,000 | 105,115 | 0.50 | 202,557 |
| Life Cycle Operations Costs | | | | $ 9,830,856 |

TABLE F-13. LIFE CYCLE OPERATING COSTS - SINGLE SITE
(400 LB/HR)

| Period | Rate, Labor $/Yr | Rate, Other $/Yr | Duration | Total Cost |
|---|---|---|---|---|
| Eq Acceptance | $ 300,000 | $ 265,742 | 0.5 | $ 282,871 |
| Training | 900,000 | 398,613 | 0.5 | 649,307 |
| Inventory Item A | 900,000 | 797,227 | 0.62 | 1,052,281 |
| Change Out | 900,000 | 398,613 | 0.17 | 220,784 |
| Inventory Item B/C | 900,000 | 797,227 | 0.83 | 1,408,698 |
| Change Out | 900,000 | 398,613 | 0.17 | 220,764 |
| Inventory Item D | 900,000 | 797,227 | 0.25 | 424,307 |
| Scheduled Maintenance | 900,000 | 398,613 | 0.11 | 142,847 |
| Shutdown | 300,000 | 265,742 | 0.5 | 282,871 |
| Life Cycle Operations Costs | | | | $ 4,684,730 |

TABLE F-14. LIFE CYCLE OPERATING COSTS - SINGLE SITE
(1000 LB/HR)

| Period | Labor $/Yr | Other $/Yr | Rate, Duration | Total Cost |
|---|---|---|---|---|
| Eq Acceptance | $ 400,000 | $ 562,504 | 0.5 | $ 481,252 |
| Training | 1,200,000 | 843,755 | 0.5 | 1,021,878 |
| Inventory Item A | 1,200,000 | 1,687,511 | 0.25 | 721,878 |
| Change Out | 1,200,000 | 843,755 | 0.17 | 347,438 |
| Inventory Item B/C | 1,200,000 | 1,687,511 | 0.34 | 981,753 |
| Change Out | 1,200,000 | 843,755 | 0.17 | 347,438 |
| Inventory Item D | 1,200,000 | 1,687,511 | 0.11 | 317,626 |
| Scheduled Maintenance | 1,200,000 | 843,755 | 0.06 | 122,625 |
| Shutdown | 400,000 | 562,504 | 0.5 | 481,252 |
| Life Cycle Operations Costs | | | | $ 4,823,140 |

TABLE F-15. LIFE CYCLE OPERATING COSTS - COLLOCATED SITE (400 LB/HR)

| Period | Rate, Labor $/Yr | Rate, Other $/Yr | Duration | Total Cost |
|---|---|---|---|---|
| Eq Acceptance | $ 300,000 | $ 275,742 | 0.5 | $ 287,871 |
| Training | 900,000 | 413,613 | 0.5 | 656,807 |
| Inventory Item A | 900,000 | 827,227 | 6.18 | 10,674,263 |
| Change Out | 900,000 | 413,613 | 0.17 | 223,314 |
| Inventory Item B/C | 900,000 | 827,227 | 10.50 | 18,135,884 |
| Change Out | 900,000 | 413,613 | 0.17 | 223,314 |
| Inventory Item D | 900,000 | 827,227 | 2.58 | 4,456,246 |
| Scheduled Maintenance | 900,000 | 413,613 | 1.04 | 1,366,158 |
| Shutdown | 300,000 | 275,742 | 0.5 | 287,871 |
| Life Cycle Operations Costs | | | | $36,311,728 |

TABLE F-16. LIFE CYCLE OPERATING COSTS - COLLOCATED SITE
(1000 LB/HR)

| Period | Rate, Labor $/Yr | Rate, Other $/Yr | Duration | Total Cost |
|---|---|---|---|---|
| Eq Acceptance | $ 400,000 | $ 562,504 | 0.5 | $ 481,252 |
| Training | 1,200,000 | 843,756 | 0.5 | 1,021,878 |
| Inventory Item A | 1,200,000 | 1,657,511 | 2.47 | 7,132,152 |
| Change Out | 1,200,000 | 843,756 | 0.17 | 347,438 |
| Inventory Item B/C | 1,200,000 | 1,687,511 | 3.32 | 9,586,537 |
| Change Out | 1,200,000 | 843,756 | 0.17 | 347,438 |
| Inventory Item D | 1,200,000 | 1,687,511 | 1.06 | 3,060,762 |
| Scheduled Maintenance | 1,200,000 | 843,756 | 0.548 | 1,119,978 |
| Shutdown | 400,000 | 562,504 | 0.5 | 481,252 |
| Life Cycle Operations Costs | | | | $23,578,687 |

TABLE F-17. LIFE CYCLE OPERATING COSTS - COLLOCATED SITE
(3000 LB/HR)

| Period | Rate, Labor $/Yr | Rate, Other $/Yr | Duration | Total Cost |
|---|---|---|---|---|
| Eq Acceptance | $ 500,000 | $1,503,440 | 0.5 | $ 1,001,720 |
| Training | 1,500,000 | 2,255,161 | 0.5 | 1,877,580 |
| Inventory Item A | 1,500,000 | 4,510,321 | 0.81 | 4,868,360 |
| Change Out | 1,500,000 | 2,255,161 | 0.17 | 638,377 |
| Inventory Item B/C | 1,500,000 | 4,510,321 | 1.10 | 6,611,353 |
| Change Out | 1,500,000 | 2,255,161 | 0.17 | 638,377 |
| Inventory Item D | 1,500,000 | 4,510,321 | 0.368 | 2,211,798 |
| Scheduled Maintenance | 1,500,000 | 2,255,161 | 0.194 | 728,501 |
| Shutdown | 500,000 | 1,503,440 | 0.5 | 1,001,720 |
| Life Cycle Operations Costs | | | | $19,577,786 |

TABLE F-18. LIFE CYCLE OPERATING COSTS - COLLOCATED SITE
(5000 LB/HR)

| Period | Rate, Labor $/Yr | Rate, Other $/Yr | Duration | Total Cost |
|---|---|---|---|---|
| Eq Acceptance | $ 600,000 | $2,443,700 | 0.5 | $ 1,521,850 |
| Training | 1,800,000 | 3,665,551 | 0.5 | 2,738,331 |
| Inventory Item A | 1,800,000 | 7,331,101 | 0.49 | 4,474,240 |
| Change Out | 1,800,000 | 3,665,551 | 0.17 | 931,032 |
| Inventory Item B/C | 1,800,000 | 7,331,101 | 0.66 | 6,026,527 |
| Change Out | 1,800,000 | 3,665,551 | 0.17 | 931,032 |
| Inventory Item D | 1,800,000 | 7,331,101 | 0.22 | 2,008,842 |
| Scheduled Maintenance | 1,800,000 | 3,665,551 | 0.123 | 673,629 |
| Shutdown | 600,000 | 2,443,700 | 0.5 | 1,521,850 |
| Life Cycle Operations Costs | | | | $20,827,333 |

TABLE F-19. DEVELOPMENT COSTS

| | |
|---|---|
| Phase II - Bench Scale | |
| Concept Refinement | $ 15,000 |
| Incineration Pyrolysis Studies | 150,000 |
| Refractory-Materials Compatibility Studies | 150,000 |
| Environmental Studies | 160,000 |
| Feasibility Studies | 75,000 |
| Conceptual Design Studies | 50,000 |
| Materials | 150,000 |
| Subcontractors | 150,000 |
| Contingencies | 60,000 |
| TOTAL PHASE II DEVELOPMENT COSTS | $ 960,000 |
| Phase III - Pilot Studies | |
| Pilot Plant Design | $ 300,000 |
| Test Plans and Operations Procedures | 60,000 |
| Pilot Plant Construction | 1,395,000 |
| Pilot Plant Startup | 114,000 |
| Operator Training | 300,000 |
| Pilot Plant Operation | 682,000 |
| Test Report | 15,000 |
| Process Development Program | 600,000 |
| 30% Design Package | 400,000 |
| Subcontractors | 500,000 |
| Contingencies (20%) | 873,000 |
| TOTAL PHASE III DEVELOPMENT COSTS | $5,239,000 |
| TOTAL DEVELOPMENT COSTS | $6,199,000 |

TABLE F-20. TOTAL COST ESTIMATES - SINGLE SITE

| Cost Item | Agent Rate (lb/hr) 100 lb/hr | 400 lb/hr | 1000 lb/hr |
|---|---|---|---|
| Facility Costs | $ 1,235,900 | $ 1,273,000 | $ 2,019,000 |
| Capital Equipment Costs | 1,665,750 | 3,310,500 | 5,563,750 |
| Life Cycle Operations Costs | 9,830,856 | 4,684,730 | 4,823,142 |
| Development Costs | 6,199,000 | 6,199,000 | 6,199,000 |
| TOTAL COSTS | $18,930,606 | $15,467,230 | $18,604,892 |

TABLE F-21. TOTAL COST ESTIMATES - COLLOCATED SITE

| Cost Item | Agent Rate (lb/hr) 400 lb/hr | 1000 lb/hr | 3000 lb/hr | 5000 lb/hr |
|---|---|---|---|---|
| Facility Costs | $ 1,295,000 | $ 2,036,000 | $ 3,530,000 | $ 4,563,000 |
| Capital Equipment Costs | 3,310,500 | 5,563,750 | 11,559,000 | 17,188,750 |
| Life Cycle Operating Costs | 36,311,728 | 23,578,687 | 19,577,787 | 20,827,332 |
| Development Costs | 6,199,000 | 6,199,000 | 6,199,000 | 6,199,000 |
| TOTAL COSTS | $47,116,228 | $37,377,437 | $40,867,787 | $48,739,255 |

standpoint can be seen in the thermal system cost curves (Figures F-3 and F-4). These curves indicate that the optimum single site processing rate is approximately 400 pounds per hour while the optimum collocation rate appears to be slightly greater than 1000 pounds per hour. At these rates, the estimated total costs of $15,467,230 and $33,377,437 appear to offer a decided advantage over the base line cost.

## G. Operating Time

The operating times required for the various inventory categories were discussed previously. The total life cycle operating times for the various agent throughput rates are summarized in Table F-22.

FIGURE F-3

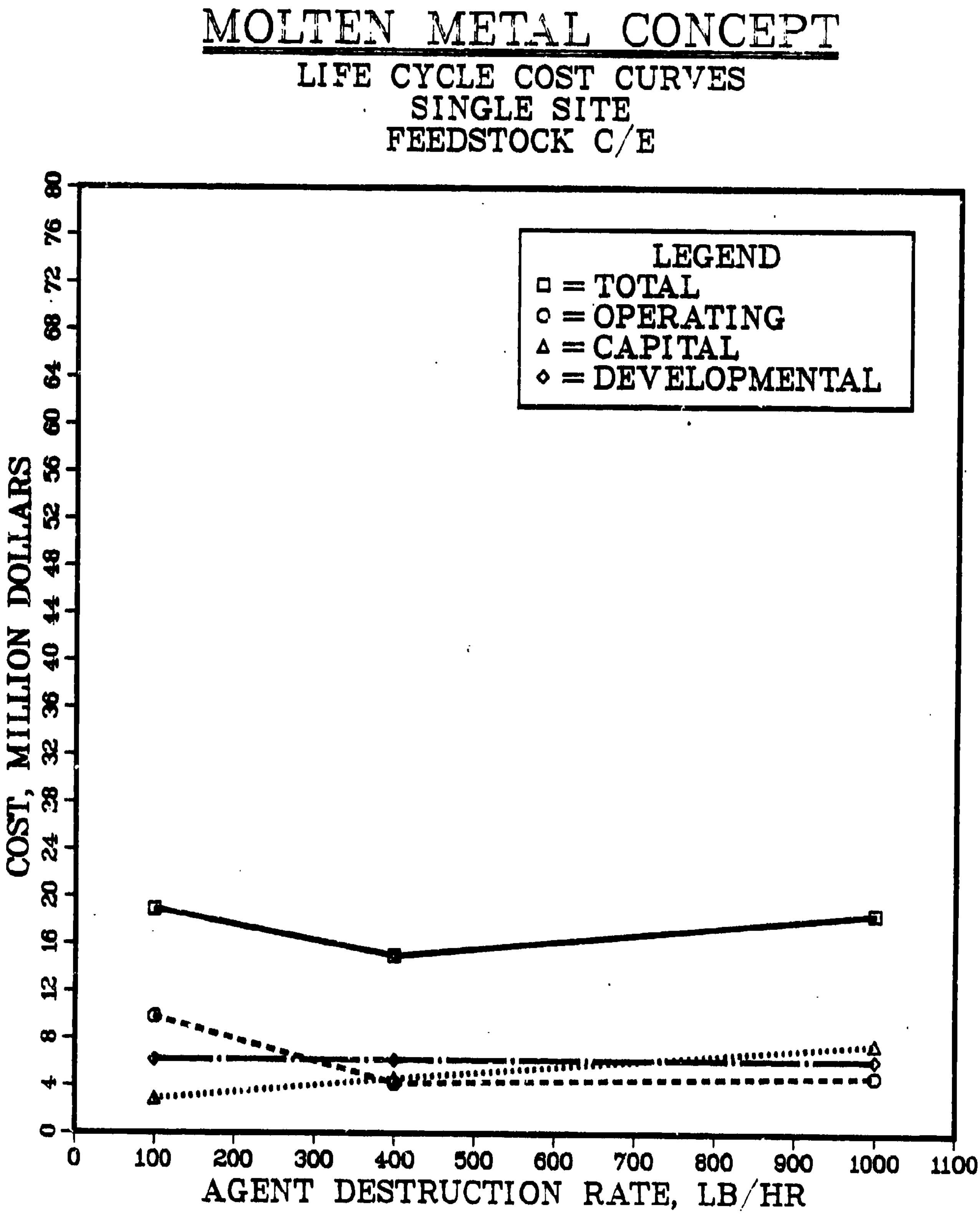
MOLTEN METAL CONCEPT
LIFE CYCLE COST CURVES
SINGLE SITE
FEEDSTOCK C/E
LEGEND
□ = TOTAL
○ = OPERATING
△ = CAPITAL
◇ = DEVELOPMENTAL
COST, MILLION DOLLARS
0 4 8 12 16 20 24 28 32 36 40 44 48 52 56 60 64 68 72 76 80
0 100 200 300 400 500 600 700 800 900 1000 1100
AGENT DESTRUCTION RATE, LB/HR

FIGURE F-4

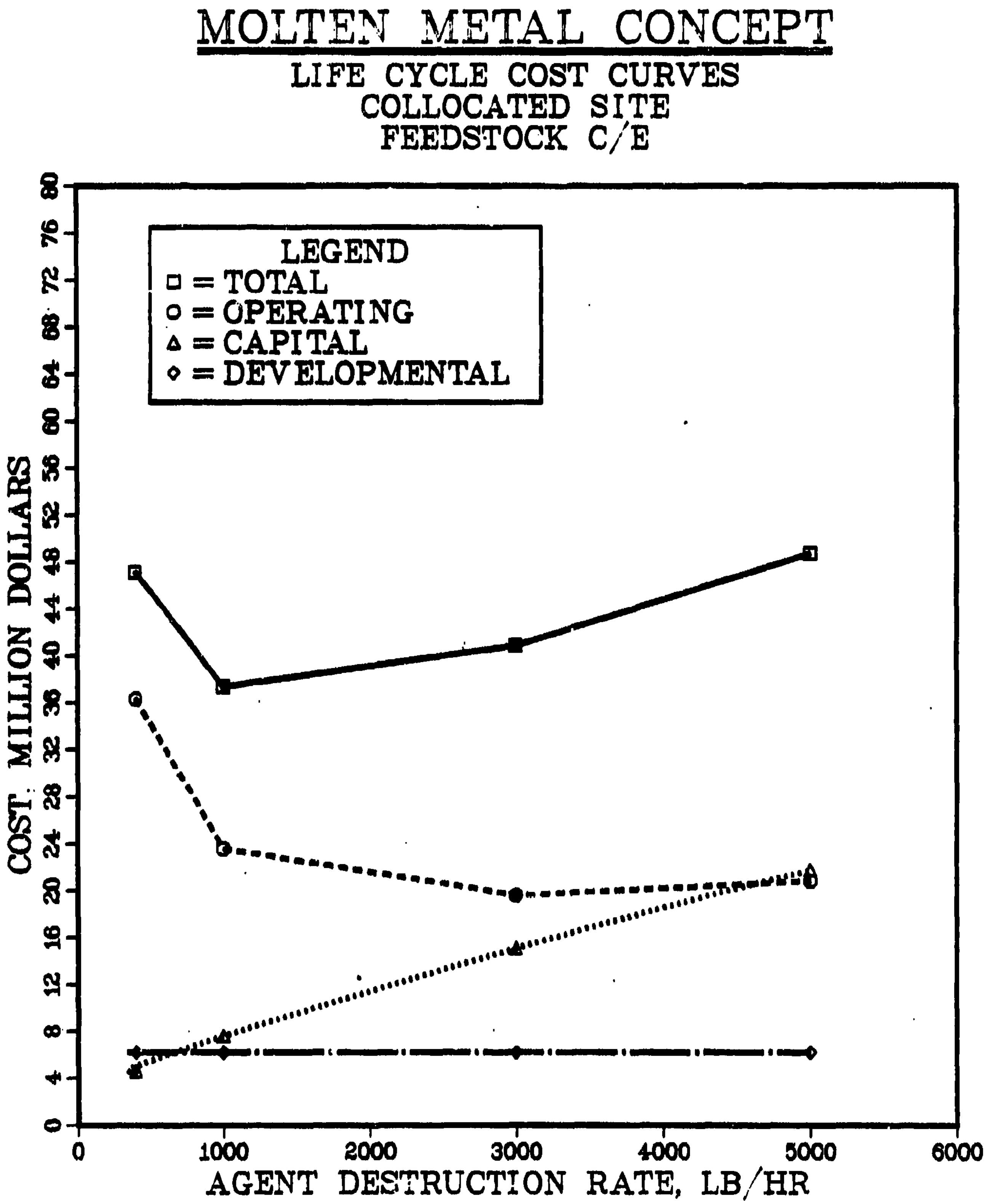
MOLTEN METAL CONCEPT
LIFE CYCLE COST CURVES
COLLOCATED SITE
FEEDSTOCK C/E
LEGEND
□ = TOTAL
○ = OPERATING
△ = CAPITAL
◇ = DEVELOPMENTAL
COST, MILLION DOLLARS
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
72
76
80
0
1000
2000
3000
4000
5000
6000
AGENT DESTRUCTION RATE, LB/HR

TABLE F-22. OPERATING TIME

| Agent Rate lb/hr | Operating Year |
|---|---|
| **Single Site** | |
| 100 | 8.91 |
| 400 | 3.65 |
| 1000 | 2.60 |
| **Collocated Site** | |
| 400 | 22.14 |
| 1000 | 9.25 |
| 3000 | 4.31 |
| 5000 | 3.33 |

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4.

5. J. Harting, D. Neushutz, D. Reed, and H. Secleo of Krupp Research Institute "New Process Developments in Melting Scrap and Sponse Iron", published in Iron and Steel Engineer (February, 1982.

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7. K. M. Guthrie, "Data and Techniques for Preliminary Capital Cost Estimating", Chemical Engineering, pp 114-142, (March 24, 1963).

8. Peters and Timmerhaus, <u>Plant Design and Economics for Chemical Engineers</u>, McGraw Hill, Second Edition.

# APPENDIX G

## ENGINEERING AND ECONOMIC ANALYSIS - FLUIDIZED-BED

# APPENDIX G

## ENGINEERING AND ECONOMIC ANALYSIS - FLUIDIZED-BED

### Engineering Analysis - Fluidized-Bed

#### A. System Concept Description

Eight fluidized-bed concepts are listed among the 44 concepts evaluated in the preliminary evaluation. Most of these eight concepts rated high. A composite engineering design is described here to show how a fluidized-bed can be effectively used to treat chemical munitions.

The fluidized-bed is capable of handling several classes of munition feed. The preliminary analysis indicated it was particularly adaptable to munitions with the explosive removed and the agent cavity opened, (configuration e) as well as for feed from a munition shredder (configuration h). However, some of the peripheral equipment requirements change with different feedstock. Costs associated with both feedstocks e and are presented later in this analysis.

Figures G-1 and G-2 are flow diagrams for three systems considered. Figure G-1 is for low feed rates (100, 400, and 1000 lb/hr) using feedstock e. Figure G-2 is for the same feedstock at rates of 3,000 and 5,000 lb/hr; Figure G-2 is also for feedstock h at all rates. The major difference between the two flow diagrams is the addition of a volatilization chamber in Figure G-1. Ton containers and other large items would be fed into this unit and the agent volatilized out. Projectiles would also be treated in the volatilization chamber when feeding 100 lb/hr of agent. The afterburner and spray dryer are similar to those used in the baseline and baseline costs are used. Material and heat balances are given in Tables G-1 and G-2.

TABLE G-1. MATERIAL BALANCE - FLUIDIZED-BED (Basis 400 lb GB)

| Material | lb |
|---|---|
| **IN** | |
| GB | 400 |
| Wood | 650 |
| Explosive-Propellent | 250 |
| Air | 16,030 |
| Water (liquid) | 5,000 |
| Metal | 2,050 |
| NaOH | 686 |
| TOTAL | 25,066 |
| **OUT** | |
| Flue gas | |
| $O_2$ | 1,867 |
| $CO_2$ | 1,983 |
| $N_2$ | 12,342 |
| $H_2O$ | 5,843 |
| Salts | |
| $Na_2HPO_4$ | 406 |
| NaF | 120 |
| $Na_2CO_3$ | 455 |
| Metal | 2050 |
| TOTAL | 25,066 |

NOTE: Fuel used only on standby.

TABLE G-2. HEAT BALANCE - FLUIDIZED-BED
(Basis 400 lb GB)

| Material | Heat of Combustion, Btu/lb | Temp. F | H, Btu |
|---|---|---|---|
| | IN | | |
| GB | 10,000 | 70 | 4,000,000 |
| Wood | 8,500 | 70 | 5,525,000 |
| Explosive | 5,400 | 70 | 1,350,000 |
| Air | | 70 | -- |
| Water | | 70 | -- |
| Metal | | 70 | -- |
| NaOH | | 70 | -- |
| Electric Energy | | | 700,000 |
| TOTAL | | | 11,575,000 |
| | OUT | | |
| Flue gas | | 270 | 7,200,000 |
| Metal | | 1,500 | 575,000 |
| Salts | | 270 | 40,000 |
| Heat losses (by difference) | | | 3,760,000 |
| TOTAL | | | 11,575,000 |

NOTE: Fuel used only on standby.
Heat of reaction to form salts from NaOH and acids neglected.

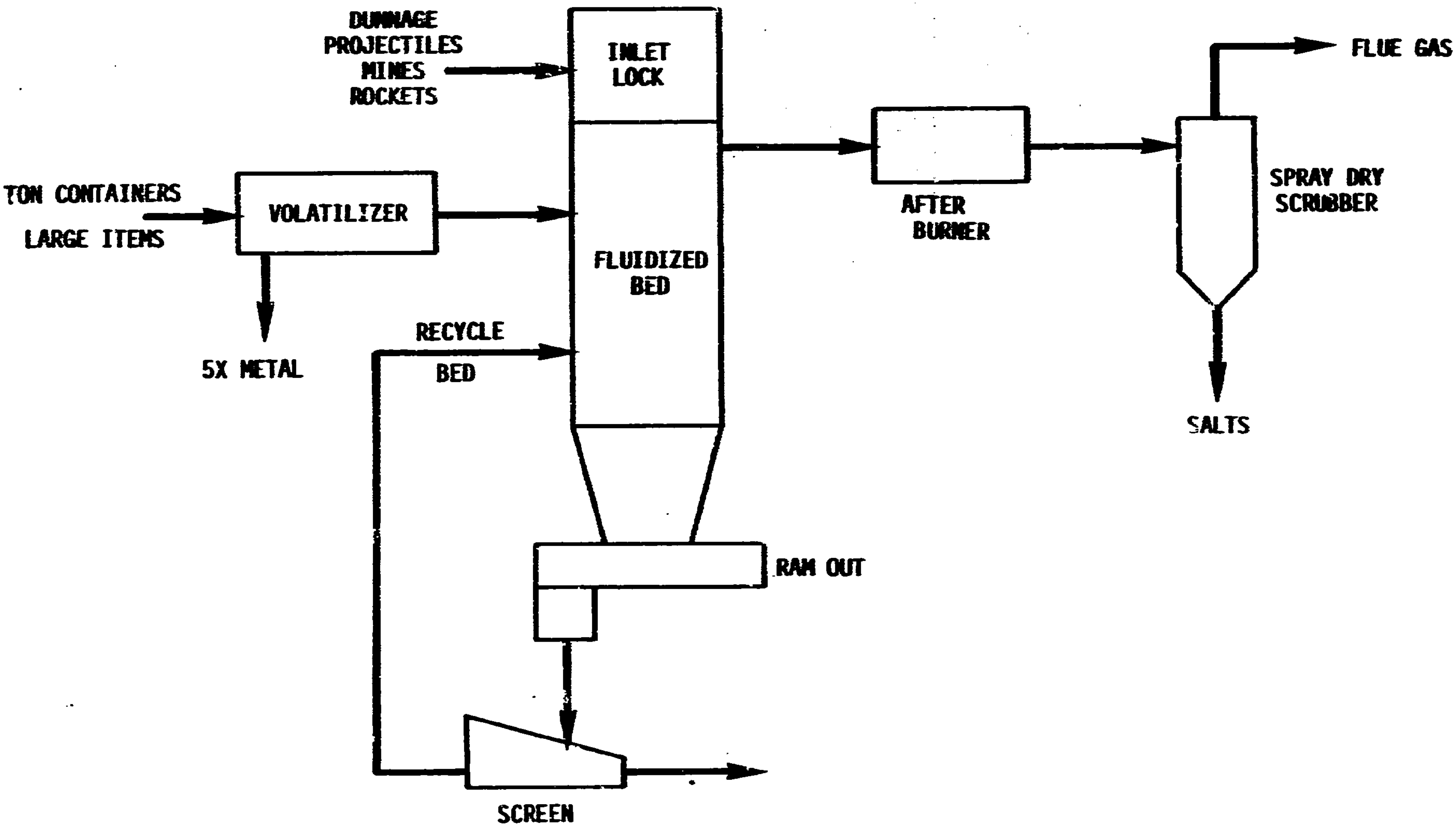



FIGURE G-1. FLUIDIZED BED CONCEPT FOR LOW RATES (FEEDSTOCK "e")

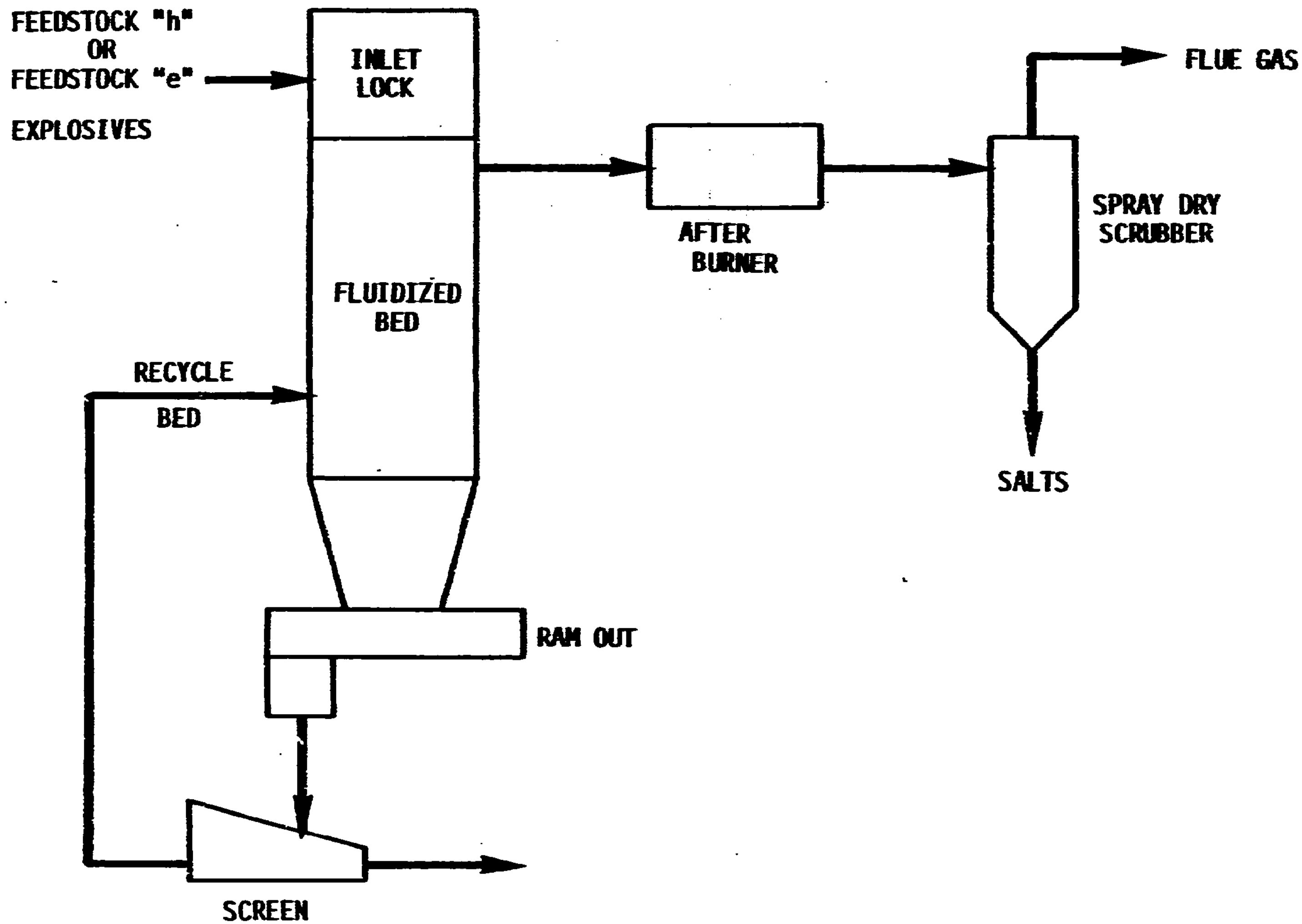



FIGURE G-2. FLUIDIZED BED CONCEPT (FEEDSTOCK "h" AND LARGE RATES OF FEEDSTOCK "e")

Referring to Figure G-1, the inlet lock is a double valve which drops the feed material into the center of the bed through the freeboard. The munition falls into the bed. The agent burns, metal is heated and decontaminated, explosives burn, and dunnage burns. The metal parts are removed through a ram-type drain in the bottom. The ram is strong enough to shear any metal caught in it. The metal and bed material drain onto a screen, the metal and bed material are separated, and the bed material returned to the bed. The metal is sold for scrap or landfilled. The afterburner and scrubber are of the baseline design.

Figure G-3 shows the internals of the fluidized bed for feedstock h. The portion of the bed above the sparger tubes is fluidized and the bed below is a moving bed. The sparger tubes are spaced to allow passage of the munitions that are being fed to the fluidized bed. As deburstered munitions are fed to the fluidized bed they will sink to the interface between the fluidized bed and the moving bed. The agent will volatilize rapidly as the munition is slowly covered by the hot bed material. As decontaminated munitions and bed material is removed from the bottom of the moving bed by the ram-type drain, the recently fed munition is progressively moved down the moving bed. The residence time of the munition body is determined by the depth of the moving bed and the bed recirculation rate. The bed material in the fluidized bed is at 1500 F or hotter; the moving bed will cool down very little since it will be well insulated. This will ensure 5x decontamination of the metal parts if the residence time of the metal parts in the moving bed is greater than 15 minutes.

At the larger feedrates, where bulk items are to be fed to the fluidized bed, the sparger air tubes will be replaced by a ring of air jets located in the sloped portion of the fluidized bed. This is shown in Figure G-4. The operation of the fluidized will be the same as with the sparger tubes.

Table G-3 gives estimated bed size parameters for several agent rates.

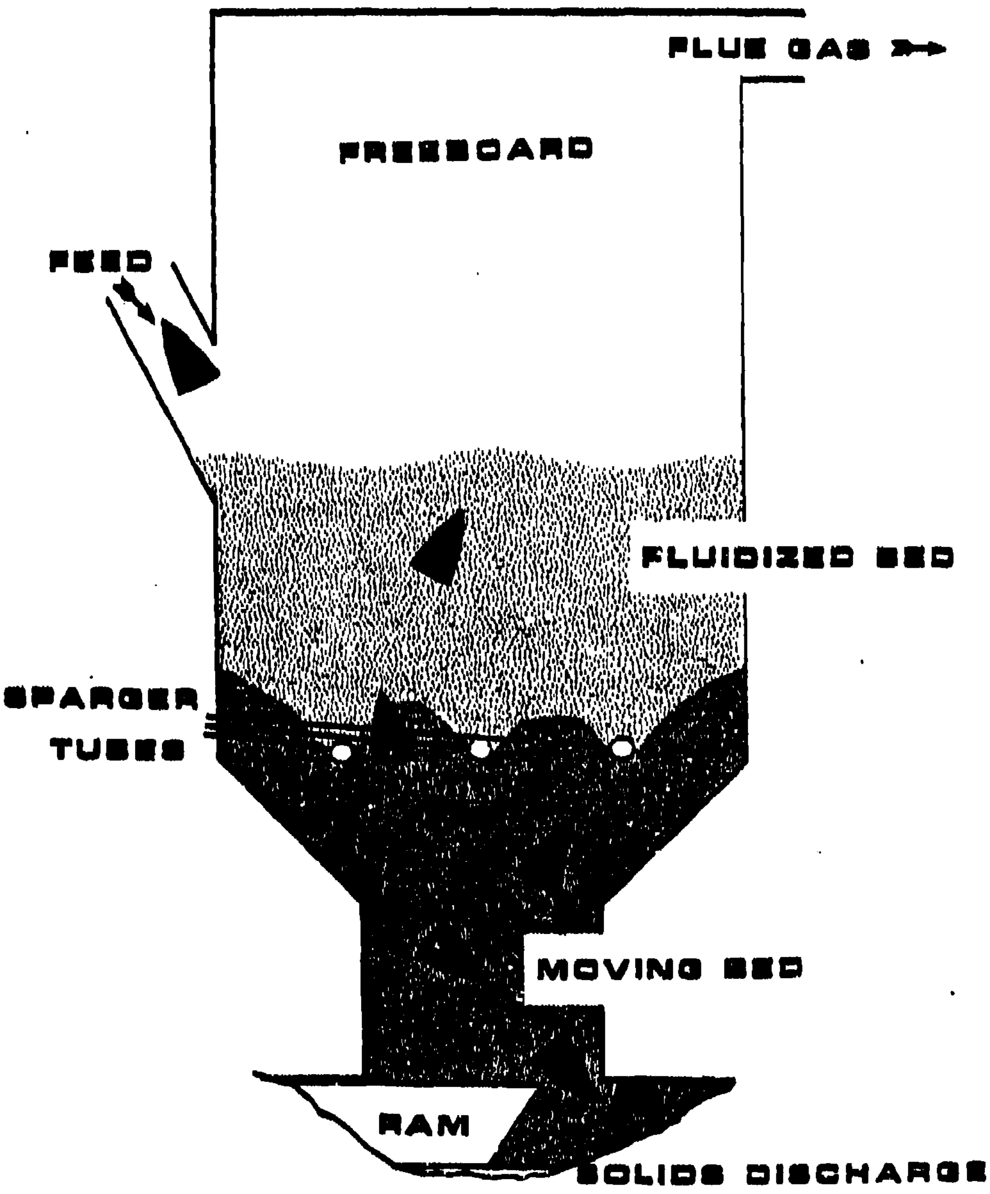



FIGURE G-3. FLUIDIZED BED INTERNALS FOR FEEDSTOCK h

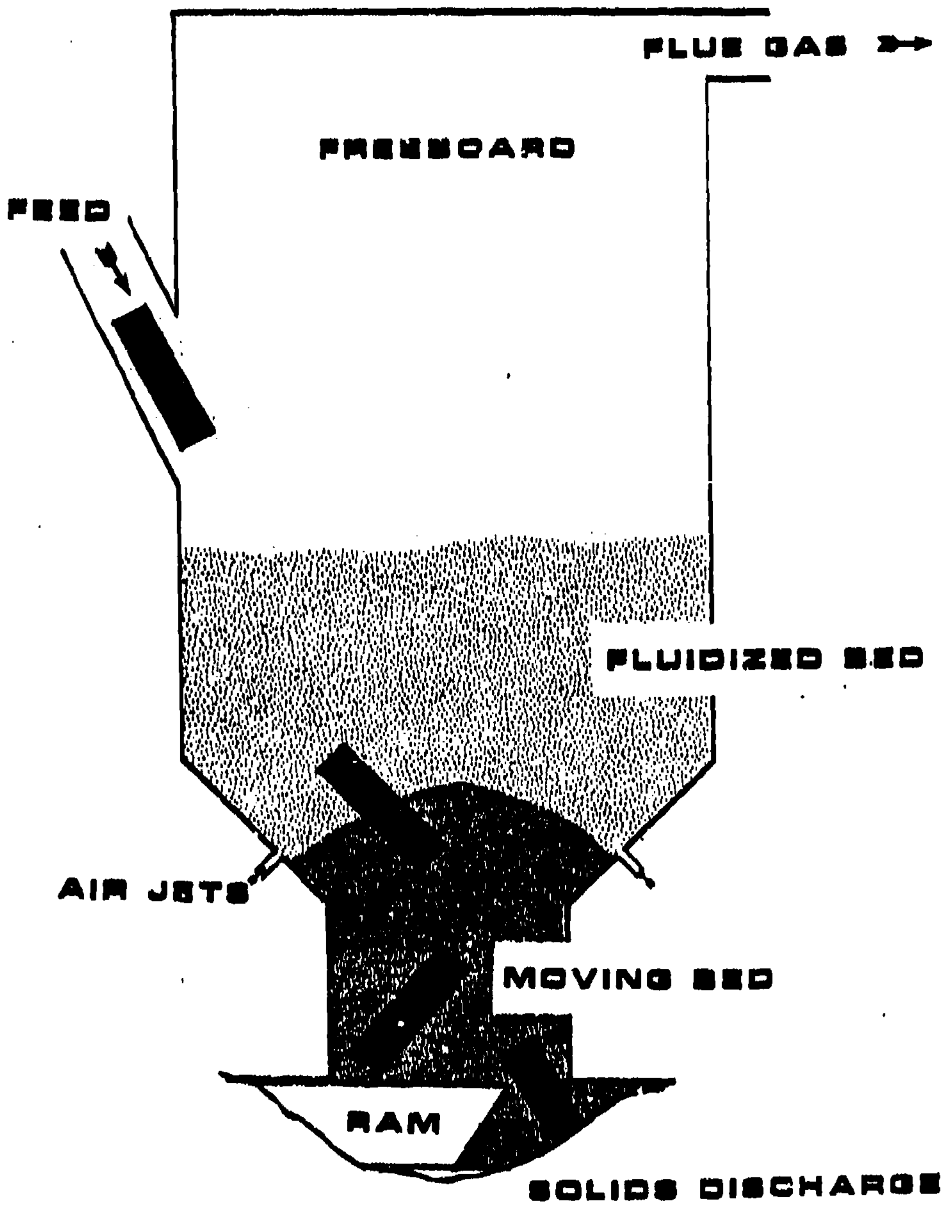



FIGURE G-4. FLUIDIZED BED INTERNALS FOR FEEDSTOCK e

TABLE G-3. FLUIDIZED-BED DESIGN PARAMETERS
(3 ft/sec, 100% Excess Air, 1500 F)

| Agent Rate, lb/hr | 100 | 400 | 1000 | 3000 | 5000 |
|---|---|---|---|---|---|
| Diameter, ft | 4.6 | 9.3 | 14.5 | 25.1 | 32.5 |
| Height, ft | 20 | 25 | 30 | 35 | 40 |
| Bed depth, ft | 4 | 5 | 5 | 6 | 6 |
| Rating, MM Btu/hr | 2.5 | 10 | 25 | 75 | 125 |
| Afterburner size, cu ft | 100 | 400 | 1000 | 3000 | 5000 |
| Air, SCFM | 850 | 3400 | 8500 | 25,500 | 42,500 |

B. System Feed Requirements

The fluidized bed system is proposed for two different feedstocks, feedstock h, and feedstock e. Feedstock e consists of munitions with the explosives removed and the agent cavity opened. The explosive, dunnage, and agent containing munitions would all be fed into the bed, possibly together but not in an assembled munition. The fluidized-bed concept can handle munitions in this configuration and also accept the dunnage and explosives removed from these munitions. A more accurate description of the applicable feed stocks is shown in Table G-4.

In all cases, the rocket motor must be made nonpropulsive. In addition, single pieces fed into the bed should not be large compared with the bed dimensions. In general, a piece should not exceed a quarter of the bed diameter. Therefore, at the 100 lb/hr agent rate, the rockets would have to be cut into four or more pieces. At the 400 lb/hr agent rate, it would have to be cut in two pieces. Projectiles would have to have their fuses and bursters removed. The large items would have to be punched open. At the 3,000 and 5,000 lb/hr rates, they can be fed directly into the bed. At the lesser rates, a volatilization chamber is needed.

TABLE G-4. DOWNLOAD NECESSARY FOR MUNITIONS FED TO FLUIDIZED-BED

| Rate, lb/hr | 100 | 400 | 1000 | 3000 | 5000 |
|---|---|---|---|---|---|
| Rockets* | 2 | 2 | 2 | 2 | 2 |
| Mines | 2 | 2 | 4 | 4 | 4 |
| Projectiles | 1 | 1 | 1 or 2 | 2 | 2 |
| Ton Containers | 3 | 3 | 3 | 3 | 3 |

*Rockets must be non-propulsive.

1 - Fuzes and bursters removed, agent cavity open.
2 - Fuzes removed, agent cavity open.
3 - Agent cavity open.
4 - No download rsquired.

NOTE: A safety analysis beyond the scope of this study is needed to demonstrate that the fluid bed can withstand the detonation of bursters without damage or that the burster will not detonate. If this cannot be demonstrated, all amunitions with fuzes and/or bursters require download 1.

C. Pollution Abatement System

The baseline pollution abatement system will be used. The dustloading will be increased slightly due to degradation of the bed material. However, the increased dust loading is not expected to require either design or cost modifications to the baseline system.

D. Ultimate Disposal

The agent combustion products will be captured in the spray dryer scrubber. Disposal will be same as baseline. The steel metal parts will be 5X decontaminated coming from the bed. They can be sold or landfilled, again the same as baseline. The aluminum metal parts will melt in the bed and agglomerate with the bed material. These agglomerates will be removed and landfilled. Since liquid aluminum has been known to detonate when in contact with water, the agglomerate handling system must not include a water quench. Otherwise, handling of the aluminum-bed agglomerates is not anticipated to be a problem.

The fluid bed, afterburner, and salt system will not be contaminated in the process and can be landfilled or sold after all munitions are treated.

E. System Concept Advantages

The major advantages of the system are in handling of material and in burning of agent and dunnage to reduce fuel usage. At higher rates, minimum downloading is used. As compared with baseline, only one thermal system is needed rather than the two systems.

Another advantage which might be applicable to the fluidized-bed systems but is not part of the system described is the use of a chemically-active bed to absorb the acidic products of agent combustion. The reasons for not including a chemically-active bed in this analysis is that it may agglomerate and cause operational problems. The residue from the active bed would probably be greater than

with the conventional scrubber, and 100 percent capture of the acidic components is not likely; thus, the conventional scrubber concept was not modified to include the active bed.

## F. System Concept Disadvantages

The system appears to be applicable to demilitarizing munitions and should work. However, it probably will not handle munitions in a configuration less downloaded than e. A demonstration of safe demilitarization of fused munitions would be very difficult. If ton containers were treated without opening them, agent probably would be released at an excessive rate when the container burst. Also unopened ton containers may explode during treatment and the final metal shape would vary. Some shapes may be difficult to remove from the bed.

## G. System Knowledge Gaps

Many knowledge gaps, which prevent a satisfactory design from being made at present, exist. Most can be eliminated by an engineering study and a few require experimental work to develop engineering parameters. Some of these knowledge gaps are:

- How can metal best be removed from the bed?
- What are effective methods of separation of metal and bed material?
- What is the effect of bed agglomeration as a result of aluminum metal?
- How can agglomeration as a result of reaction of bed material with agent combustion products be avoided?
- How much metal can be in bed before defluidizing it?
- How fast does metal heat in the bed?
- What is the agent release rate from punched ton containers?

Some experimental work is needed on removal of metal parts from the bed. Since the metal parts are denser than the bed, they will sink to the bed bottom. By removing some bed from the bottom, the metal should be removed with the bed. The present conceputal method is to fill a pocket under the bed with metal and bed material. A ram would then push metal and bed material out. The top of the ram would be strong enough to shear through ton containers, projectiles, or other metal caught between it and the bottom of the bed. The pocket in the ram would be about 5 feet in diameter by 7 feet deep for the large-size beds, and perhaps about 4 feet in diameter by 4 feet deep for the smaller beds. Modeling is needed to determine how the metal is discharged from the bed, and engineering is needed to design a ram which will shear through heavy metal. With feedstock h, the pocket in the ram can be smaller.

The aluminum metal will form agglomerates with the bed material. A study is needed to determine how large these agglomerates will be and how many the bed can contain and still remain fluidized. This information is needed to determine the rate of rocket processing in a bed of a given size and thus impacts on the economic analysis presented later.

Some experimentation or engineering analysis is needed on methods of separation of the decontaminated metal and the bed material. Presumably, a screen or magnetics might be used for separation of the iron. Since aluminum melts below bed temperature, an agglomerate of aluminum and bed material will be discharged. Some method will have to be devised to solidify the aluminum and then separate the agglomerate from the bed material. Water spray cooling can not be used because, under some conditions, liquid aluminum-water mixtures detonate.

The effect of phosphoric and hydrofluoric acids on the bed material must be determined. Both form low melting eutectics with bed material candidates. At present, bauxite is thought to be satisfactory but this should be determined experimentally in a small fluidized-bed. Since the cost of bed material is small, this knowledge gap affects costs associated with downtime during operation.

Fluidized-beds defluidize when excessive amounts of solids are in them. The amount that can be in the bed must be determined to size the bed. Another factor in determining bed size is the time for the various munitions to heat to bed temperature. Since heat transfer in the bed depends upon many variables, an experimental determination is probably necessary. This will determine how long a munition item must remain in the bed to be decontaminated.

The last knowledge gap is the release rate of agent from munitions in the fluidized-bed. For example, with the fluidized-bed designed for 3,000 lb/hr of agent, the combustion rate is determined from combustion of a dunnage-explosive-agent mix. The corresponding rate for agent combustion without dunnage or explosive is 7,500 lb/hr. The bed is designed to operate at about 100 percent excess air but can operate stoichiometric for limited periods. Thus, the actual maximum agent rate is about 15,000 lb/hr. This is the equivalent of a ton container draining in 6 minutes. If the actual drainage rate is less, ton containers can be treated in beds designed for lower rates and the volatilization chamber would not be needed at those rates.

## H. Safety

The fluidized-bed system does not pose specific safety problems over the baseline system. There is a large amount of thermal energy in a hot bed. However, this is typical of large fluidized-beds which operate safely in industry.

The baseline safety problems of handling agent and explosives and of hot surfaces are not changed by using a fluidized-bed.

## I. Likelihood of Development Within 5 Years

Fluidized-beds are presently commercial in large sizes. The work needed before design is primarily associated with defining parameters and in determining a method of removing metal from bed. These problems appear to be solvable in much less than 5 years.

J. Scalability to 400-3,000 lb/hr of Agent

Fluidized-bed systems are used in applications considerably larger than needed for chemical agents. The problems of metal in a bed and agglomeration because of molten aluminum appear to be more severe with small beds than large. Because of these problems, in this concept, large munitions are not fed into the smaller beds but rather to a volatilization chamber. No special size problems are foreseen at the operating rates of interest.

K. Degree of Technical Risk

Fluidized-beds are commercially available from several vendors. In the size required, they would be field-erected. The technology gaps are those associated with the munitions; that is, the effect of large metal pieces in the bed, the effect of phosphoric and hydrofluoric acids on the bed materials and refractories. It is very unlikely that a fluidized-bed system could not be made to work.

L. Ram Factors

Total system availability for the fluidized-bed was calculated to be 0.866. Details on the calculation are given in Appendix L.

M. Materials Compatability Problems

The major portion of the actual fluidized-bed will be refractory-lined. Refractories are available which should take the environment expected. Some work is needed to define the bed material since the bed material must not agglomerate in the environment. Alumina (bauxite) is a prime candidate. Mullite, stabilized zirconia, zircon, and spinel are other possibilities. Silica-based materials would probably be attacked by hydrofluoric acid. The scrubber material of construction will be the same as baseline.

N. Energy Requirement and Source

The major energy requirement is for fuel to keep the bed warm during standby periods of operation. Nearly any source can be used and fuel oil was assumed for the economic analysis. A fuel gas would be a little simpler to use, although a cost saving would not show up in an economic analysis of the type used here. The major fuel requirements are met by burning agent and dunnage. The heat released by this combustion is used in the spray dryer.

The other major power requirement is electrical. The fan-power for the fluidized-bed is greater than that of most other processes. In the smaller units, an electrically-heated volatilization chamber is assumed. This also uses a substantial amount of power.

O. Ease of Operation

Fluidized-bed systems can have very high operating rates. Large-cat cracking units typically run for over a year without shutdown. Large units shutdown and startup easily after a weekend. After a prolonged shutdown, a day may be needed for startup, to heat the bed slowly to prevent thermal damage to the refractories.

The fluidized-bed operation should be very flexible. Different munitions can be fed simultaneously or sequentially without interfering with bed operation. Dunnage and explosive similarly can be fed simultaneously or sequentially with munitions or with each other. The limiting factors will be a limiting heat release, and a limiting amount of tramp metal that is allowable in the bed. The maximum heat release can be double that of the rating for short periods (10-30 minutes). Feed interruptions for similar periods are not significant. Longer interruptions will require the use of auxiliary fuel. The bed is capable of operation at about one-third of design rate without the use of auxiliary fuel. One of the advantages of the fluid bed is its great flexibility.

The fluidized-bed is a reasonably simple system as presented here. The major complexities are in the removal of metal from the bed, the separation of metal from bed material, and the reinjection of bed material.

## Economic Analysis - Fluidized-Bed

### A. Facility Cost

The facility costs are presented in Table G-5 when using feedstock e. The costs are essentially identical when using feedstock h except that volatilization is not needed.

### B. Equipment Cost

Equipment costs are also shown in Table G-5. The cost of the volatilizer was estimated by a vendor (Salem Furnace Company) for a furnace capable of supplying 100 KW to the work and measuring 25 feet long by 4 feet square. Their estimate was $700,000 and $500,000 for additional identical units. This size is required for 400 lb agent/hr. The same size is required at 100 lb/hr because the size is needed to treat a spray tank. At 1,000 lb/hr, a unit 2.5 times the 400 lb/hr unit was assumed.

The fluidized-bed cost was estimated from a General Atomics estimate of $2,000,000 for a 26 MM Btu unit. This unit would treat about 1,000 lb/hr of agent. The other sizes were obtained by the 0.6 power factor. The screen cost was obtained from Peters and Timmerhouse. Tho other costs were obtained from the baseline.

### C. Operating Costs

Non-labor operating costs are presented in Table G-6. Water usage is taken from baseline. The fuel cost is for 1,000 hours of operation at standby (one-third rate). No fuel is needed during

TABLE G-5. FACILITY AND EQUIPMENT COST - FLUIDIZED-BED

| Agent Destruction Rate, lb/hr | 100 | | 400 | | 1000 | | 3000 | | 5000 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $ | ft²* | $ | ft²* | $ | ft²* | $ | ft²* | $ | ft²* |
| **Item:** | | | | | | | | | | |
| Facility | | | | | | | | | | |
| Volatilizer | 58,500 | 650 | 58,500 | 650 | 72,000 | 800 | — | — | — | — |
| Fluidized-bed | 90,000 | 225 | 360,000 | 900 | 800,000 | 2,000 | 1,440,000 | 3,600 | 2,000,000 | 5,000 |
| Screen | 9,000 | 100 | 9,000 | 100 | 27,000 | 300 | 45,000 | 500 | 63,000 | 700 |
| Spray Dry Scrubber | 3,125 | 1,250 | 6,250 | 2,500 | 9,900 | 3,950 | 17,100 | 6,840 | 21,900 | 8,830 |
| Salt & Drum Storage | 75,500 | 1,840 | 151,000 | 3,680 | 238,000 | 5,800 | 412,000 | 10,000 | 532,000 | 12,900 |
| Fuel Tank Pad | 1,650 | 660 | 3,300 | 1,320 | 5,250 | 2,100 | 9,090 | 3,640 | 11,700 | 4,700 |
| TOTAL | 238,000 | | 588,000 | | 1,152,000 | | 1,923,000 | | 2,629,000 | |
| Equipment | | | | | | | | | | |
| Volatilizer | 700,000 | | 700,000 | | 1,500,000 | | — | | — | |
| Fluidized-bed | 500,000 | | 1,150,000 | | 2,000,000 | | 3,900,000 | | 5,250,000 | |
| Screen | 9,300 | | 30,000 | | 75,000 | | 225,000 | | 375,000 | |
| Spray Dry Scrubber | 137,000 | | 295,000 | | 488,000 | | 893,000 | | 1,183,000 | |
| Storage Forklift | 6,300 | | 14,500 | | 25,000 | | 48,500 | | 66,000 | |
| Fuel Tanks | 18,000 | | 36,000 | | 72,000 | | 144,000 | | 180,000 | |
| Residue Handling Truck | 65,000 | | 65,000 | | 130,000 | | 195,000 | | 650,000 | |
| Baghouse | 65,000 | | 170,000 | | 323,000 | | 700,000 | | 1,000,000 | |
| SUBTOTAL | 1,501,000 | | 2,460,000 | | 4,614,000 | | 6,105,000 | | 8,704,000 | |
| Design 25% | 435,000 | | 762,000 | | 1,442,000 | | 2,003,000 | | 2,829,000 | |
| TOTAL CAPITAL | 2,174,000 | | 3,810,000 | | 7,208,000 | | 10,031,000 | | 14,162,000 | |

*Facility area.

## TABLE G-6. DIRECT COSTS - FLUIDIZED-BED
## $/YEAR

| Agent Rate, lb/hr | | 100 | 400 | 1000 | 3000 | 5000 |
|---|---|---|---|---|---|---|
| Water, $10^6$ gal/year | | 6 | 12 | 19 | 31.0 | 40.0 |
| $0.53/1000 gal (Baseline) | | 3,180 | 6,360 | 10,000 | 16,700 | 21,000 |
| Electric, $10^6$ KWH/year - | Feed e | 0.86 | 2.13 | 4.74 | 11.04 | 17.7 |
| | Feed h | 0.61 | 1.9 | 4.14 | 11.04 | 17.7 |
| $0.05/KWH - | Feed e | 43,000 | 106,500 | 237,000 | 552,000 | 883,000 |
| | Feed h | 30,600 | 95,000 | 207,000 | 5552,000 | 883,000 |
| Fuel, gal/year* | | 22,500 | 90,000 | 225,000 | 675,000 | 1,125,000 |
| $1.20/gal | | 27,000 | 107,000 | 268,000 | 800,000 | 1,338,000 |
| TOTAL | Feed e | 73,200 | 220,000 | 515,000 | 1,369,000 | 2,242,000 |
| | Feed h | 60,800 | 208,000 | 485,000 | 1,368,000 | 2,242,000 |
| Other Direct Cost | | | | | | |
| Spare parts, 6% Capital/year | | 130,000 | 229,000 | 432,000 | 600,000 | 850,000 |
| Material, 10% Other operating | | 97,000 | 157,000 | 230,000 | 332,000 | 420,000 |
| TOTAL Non-Labor Operating Cost | | | | | | |
| | Feed e | 300,000 | 606,000 | 1,117,000 | 2,301,000 | 3,512,000 |
| | Feed h | 288,000 | 594,000 | 1,147,000 | 2,301,000 | 3,512,000 |

*Fuel not needed for operation with normal mix. Fuel cost is based on operating standby for 1000 hr/year.

normal operation as the heat of combustion of agent, dunnage, and explosives is adequate to maintain bed temperature. The material and spare parts costs were taken as a percentage of capital and other operating costs as was done in the baseline.

The electric power costs are detailed in Table G-7. The fluidized-bed costs are for operating the forced and induced draft fans. They are proportional to feed rate since the air flow is proportional to feed rate. The volatilizer cost is to electrically heat the large items to 1,000 F. The heat of vaporization of the agent is expected to come from combustion of agent. At the 100 lb/hr rate, projectiles as well as ton containers are treated in the volatilizer. The salt equipment cost is taken from baseline.

Estimated labor requirements are presented in Table G-8. The cost of a man-year is taken as $50,000. The personnel shown are only for the maintenance and operation of the thermal system. Overhead and mechanical preparation functions are not included.

Table G-9 is a summary of the operating costs. Operational time was taken assuming a RAM factor of 0.866. The other times were taken from baseline. The fractional decrease in operating costs during equipment acceptance, training, changeout, and shutdown were taken from baseline.

## D. Development Cost

An estimate of the developmental cost is presented in Table G-10.

## E. Total Costs

The total cost for disposal of the inventory is present in Table G-11. These are the sums of the costs developed in Tables G-5, G-9, and G-10. The Thermal Systems Concept costs are shown in Figures G-5 through G-8.

TABLE G-7. ELECTRIC POWER COSTS - FLUIDIZED-BED $/YEAR

| Agent Rate, lb/hr | 100 | 400 | 1000 | 3000 | 5000 |
|---|---|---|---|---|---|
| Fluidized bed | 14,100 | 57,000 | 141,000 | 425,000 | 710,000 |
| Volatilizer* | 12,400 | 11,500 | 30,000 | 0 | 0 |
| Salt equipment | 16,500 | 38,000 | 66,000 | 127,000 | 173,000 |
| Total, feedstock e | 43,000 | 106,500 | 237,000 | 552,000 | 883,000 |
| Total, feedstock h | 30,600 | 95,000 | 207,000 | 552,000 | 883,000 |

*Feedstock e only.

TABLE G-8. LABOR REQUIREMENTS - FLUIDIZED-BED

| Agent Rate, lb/hr | 100 | 400 | 1000 | 3000 | 5000 |
|---|---|---|---|---|---|
| Fluidized- bed operator, men/shift | 1 | 2 | 2 | 2 | 2 |
| Maintenance, men/shift | 1 | 1 | 2 | 2 | 2 |
| Control room, men/shift | 1 | 1 | 1 | 1 | 1 |
| Pollution abatement, men/shift | 1 | 1 | 1 | 2 | 2 |
| Ultimate disposal, men/shift | 2 | 4 | 6 | 6 | 6 |
| Total/shift | 6 | 9 | 12 | 13 | 13 |
| Man-years/year | 18 | 27 | 36 | 39 | 39 |
| Labor cost, $/year | 900,000 | 1,350,000 | 1,800,000 | 1,950,000 | 1,950,000 |

TABLE G-9. LIFE CYCLE OPERATING COSTS - FLUIDIZED-BED

| Agent Rate, lb/hr | 100 lb/hr, Single Site | | | | 400 lb/hr, Single Site | | | | 1000 lb/hr, Single Site | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Duration year | Annual Labor Cost, $/yr | Other Annual Cost, $/yr | Total Cost, $ | Duration, year | Annual Labor Cost, $/yr | Other Annual Cost, $/yr | Total Cost, $ | Duration, year | Annual Labor Cost, $/yr | Other Annual Cost, $/yr | Total Cost, $ |
| Equipment Acceptance | 0.5 | 300,000 | 100,000 | 200,000 | 0.5 | 450,000 | 202,000 | 326,000 | 0.5 | 600,000 | 392,000 | 496,000 |
| Training | 0.5 | 900,000 | 150,000 | 525,000 | 0.5 | 1,350,000 | 303,000 | 827,000 | 0.5 | 1,800,000 | 589,000 | 1,194,000 |
| Operation - Miners and rockets | 2.48 | 900,000 | 300,000 | 2,976,000 | 0.61 | 1,350,000 | 606,000 | 1,193,000 | 0.22 | 1,800,000 | 1,177,000 | 744,000 |
| Changeout | 0.17 | 900,000 | 150,000 | 178,000 | 0.17 | 1,350,000 | 303,000 | 281,000 | 0.17 | 1,800,000 | 589,000 | 406,000 |
| Operation - Projectiles | 3.3 | 900,000 | 300,000 | 3,960,000 | 0.82 | 1,350,000 | 606,000 | 1,604,000 | 0.33 | 1,800,000 | 1,177,000 | 9,820,000 |
| Changeout | 0.17 | 900,000 | 150,000 | 178,000 | 0.17 | 1,350,000 | 303,000 | 281,000 | 0.17 | 1,800,000 | 589,000 | 406,000 |
| Operation - Bulk items | 1.1 | 900,000 | 300,000 | 1,320,000 | 0.28 | 1,350,000 | 606,000 | 548,000 | 0.11 | 1,800,000 | 1,177,000 | 327,000 |
| Shutdown | 0.5 | 300,000 | 100,000 | 200,000 | 0.5 | 450,000 | 202,000 | 326,000 | 0.5 | 600,000 | 392,000 | 496,000 |
| TOTAL | 8.72 | | | 9,537,000 | 3.55 | | | 5,386,000 | 2.53 | | | 5,051,000 |

TABLE 6-9, continued

| Agent Rate, lb/hr | 1000 lb/hr, Collocated | | | | 3000 lb/hr, Collocated | | | | 5000 lb/hr, Collocated | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Duration year | Annual Labor Cost, $/yr | Other Annual Cost, $/yr | Total Cost, $ | Duration, year | Annual Labor Cost, $/yr | Other Annual Cost, $/yr | Total Cost, $ | Duration, year | Annual Labor Cost, $/yr | Other Annual Cost, $/yr | Total Cost, $ |
| Equipment Acceptance | 0.5 | 600,000 | 392,000 | 496,000 | 0.5 | 650,000 | 767,000 | 708,000 | 0.5 | 650,000 | 1,171,000 | 910,000 |
| Training | 0.5 | 1,800,000 | 589,000 | 1,194,000 | 0.5 | 1,950,000 | 1,151,000 | 1,551,000 | 0.5 | 1,950,000 | 1,756,000 | 1,853,000 |
| Operation - Miners and rockets | 2.48 | 1,800,000 | 1,177,000 | 7,440,000 | 0.83 | 1,950,000 | 2,301,000 | 3,528,000 | 0.5 | 1,950,000 | 3,512,000 | 2,731,000 |
| Changeout | 0.17 | 1,800,000 | 589,000 | 406,000 | 0.17 | 1,950,000 | 1,151,000 | 527,000 | 0.17 | 1,950,000 | 1,756,000 | 630,000 |
| Operation - Projectiles | 3.3 | 1,800,000 | 1,177,000 | 9,820,000 | 1.1 | 1,950,000 | 2,301,000 | 4,676,000 | 0.67 | 1,950,000 | 3,512,000 | 3,660,000 |
| Changeout | 0.17 | 1,800,000 | 589,000 | 406,000 | 0.17 | 1,950,000 | 1,151,000 | 527,000 | 0.17 | 1,950,000 | 1,756,000 | 630,000 |
| Operation - Bulk items | 1.1 | 1,800,000 | 1,177,000 | 3,270,000 | 0.37 | 1,950,000 | 2,301,000 | 1,573,000 | 0.22 | 1,950,000 | 3,512,000 | 1,202,000 |
| Shutdown | 0.5 | 600,000 | 392,000 | 496,000 | 0.5 | 650,000 | 767,000 | 708,000 | 0.5 | 650,000 | 1,756,000 | 910,000 |
| TOTAL | 8.72 | | | 23,528,000 | 4.14 | | | 13,798,000 | 3.23 | | | 12,526,000 |

TABLE G-10. DEVELOPMENT COSTS - FLUIDIZED-BED

| | Feed e | Feed h |
|---|---|---|
| Lab Scale Test Program | $ | $ |
| Labor and Fee | 600,000 | 600,000 |
| Materials | 150,000 | 150,000 |
| Subcontractors | 150,000 | 150,000 |
| Contingencies | 60,000 | 60,000 |
| TOTAL LAB SCALE | 960,000 | 960,000 |
| Pilot Plant Test Program | | |
| Conceptual Design | 250,000 | 250,000 |
| Test Plan | 40,000 | 40,000 |
| Pilot Plant | | |
| Construction | 1,255,000 | 817,000 |
| Startup | | |
| Training | 303,000 | 303,000 |
| Operation (1 yr) | 692,000 | 692,000 |
| Process Development | 3,700,000 | 3,700,000 |
| Subtotal | 6,240,000 | 5,802,000 |
| Contingencies | 1,248,000 | 1,160,000 |
| TOTAL PILOT PLANT | 7,488,000 | 6,962,000 |
| TOTAL DEVELOPMENT COST | 8,448,000 | 7,922,000 |

TABLE G-11. TOTAL COST SUMMARY - FLUIDIZED-BED

| | Single Site | | | Collocated | | |
|---|---|---|---|---|---|---|
| | 100 lb/hr | 400 lb/hr | 1000 lb/hr | 1000 lb/hr | 3000 lb/hr | 5000 lb/hr |
| | | | | Feedstock e | | |
| Capital, $ | 2,174,000 | 3,810,000 | 7,208,000 | 7,208,000 | 10,031,000 | 14,162,000 |
| Operating, $ | 9,537,000 | 5,386,000 | 5,051,000 | 23,528,000 | 13,798,000 | 12,526,000 |
| Development, $ | 8,448,000 | 8,448,000 | 8,448,000 | 8,448,000 | 8,448,000 | 8,448,000 |
| TOTAL LIFE CYCLE, $ | 20,159,000 | 17,644,000 | 20,707,000 | 39,184,000 | 32,277,000 | 35,136,000 |
| | | | | Feedstock h | | |
| Capital, $ | 1,224,000 | 2,863,000 | 5,636,000 | 5,636,000 | 10,031,000 | 14,162,000 |
| Operating, $ | 9,446,000 | 5,375,000 | 5,032,000 | 23,299,000 | 13,798,000 | 12,526,000 |
| Development, $ | 7,922,000 | 7,922,000 | 7,922,000 | 7,922,000 | 7,922,000 | 7,922,000 |
| TOTAL, LIFE CYCLE $ | 18,592,000 | 16,160,000 | 18,590,000 | 36,357,000 | 31,751,000 | 34,610,000 |

FIGURE G-5

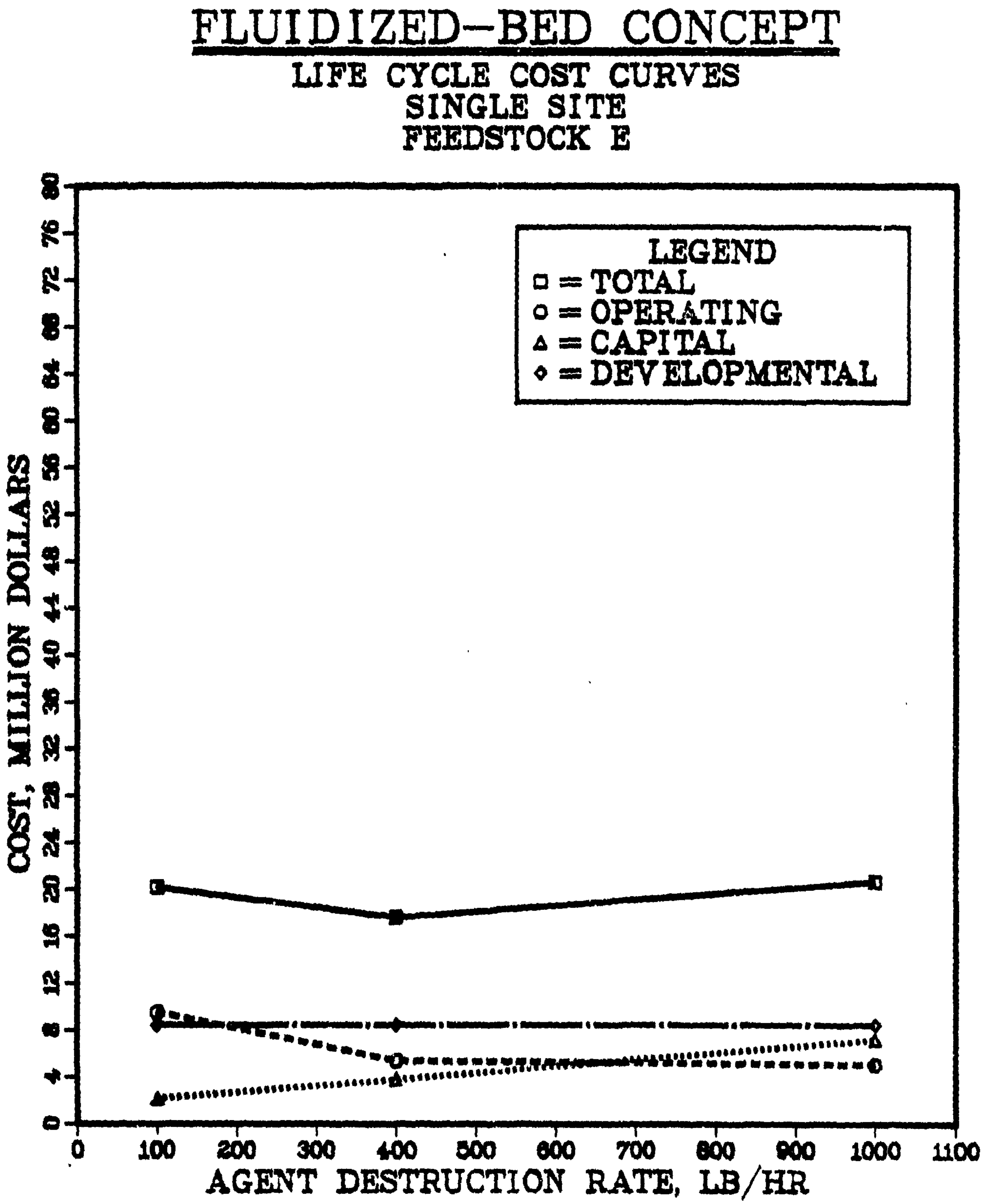

FLUIDIZED-BED CONCEPT
LIFE CYCLE COST CURVES
SINGLE SITE
FEEDSTOCK E
LEGEND
□ = TOTAL
○ = OPERATING
△ = CAPITAL
◇ = DEVELOPMENTAL
COST, MILLION DOLLARS
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
72
76
80
0
100
200
300
400
500
600
700
800
900
1000
1100
AGENT DESTRUCTION RATE, LB/HR

FIGURE G-6

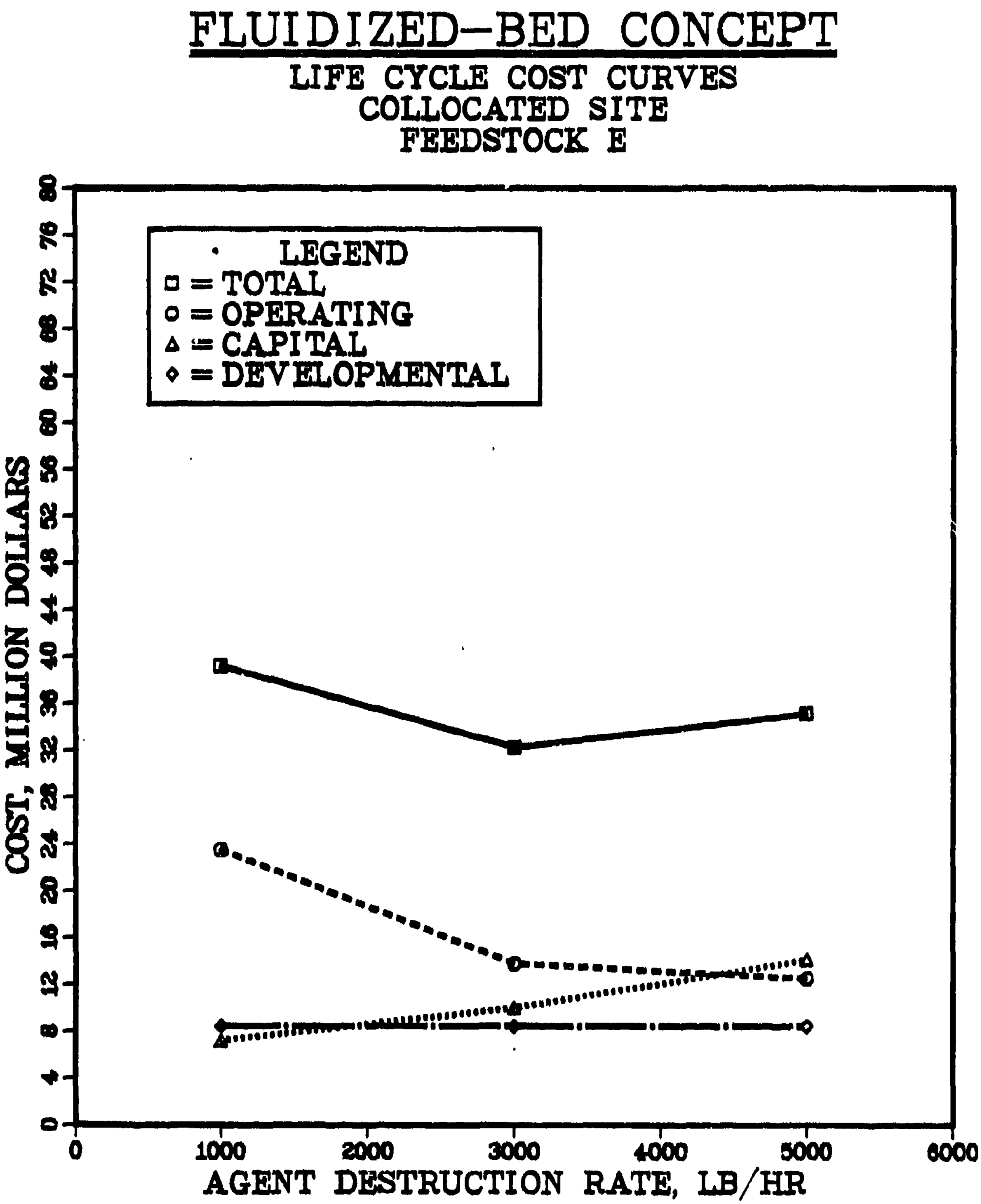

FLUIDIZED-BED CONCEPT
LIFE CYCLE COST CURVES
COLLOCATED SITE
FEEDSTOCK E
LEGEND
□ = TOTAL
○ = OPERATING
△ = CAPITAL
◇ = DEVELOPMENTAL
COST, MILLION DOLLARS
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
72
76
80
0
1000
2000
3000
4000
5000
6000
AGENT DESTRUCTION RATE, LB/HR

FIGURE G-7

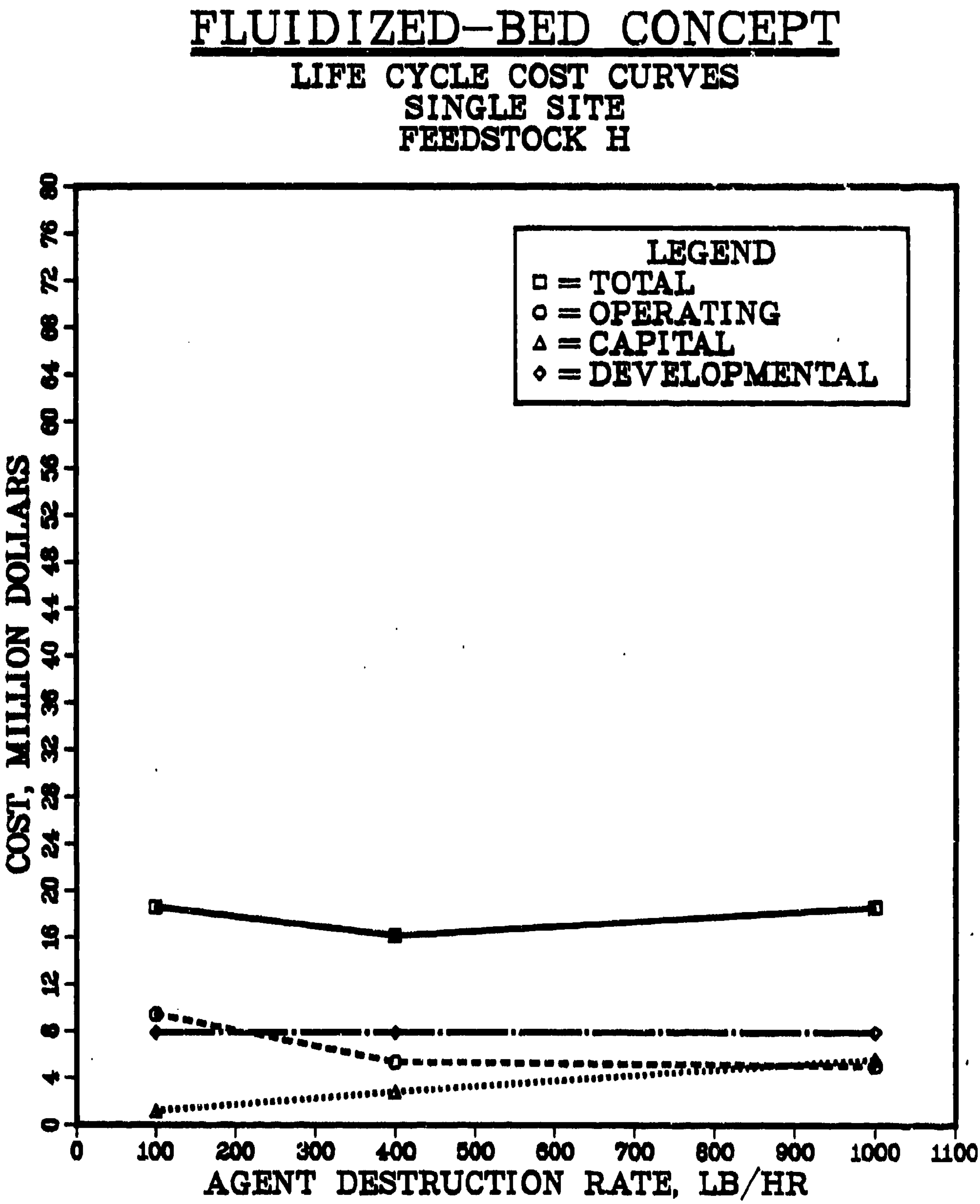
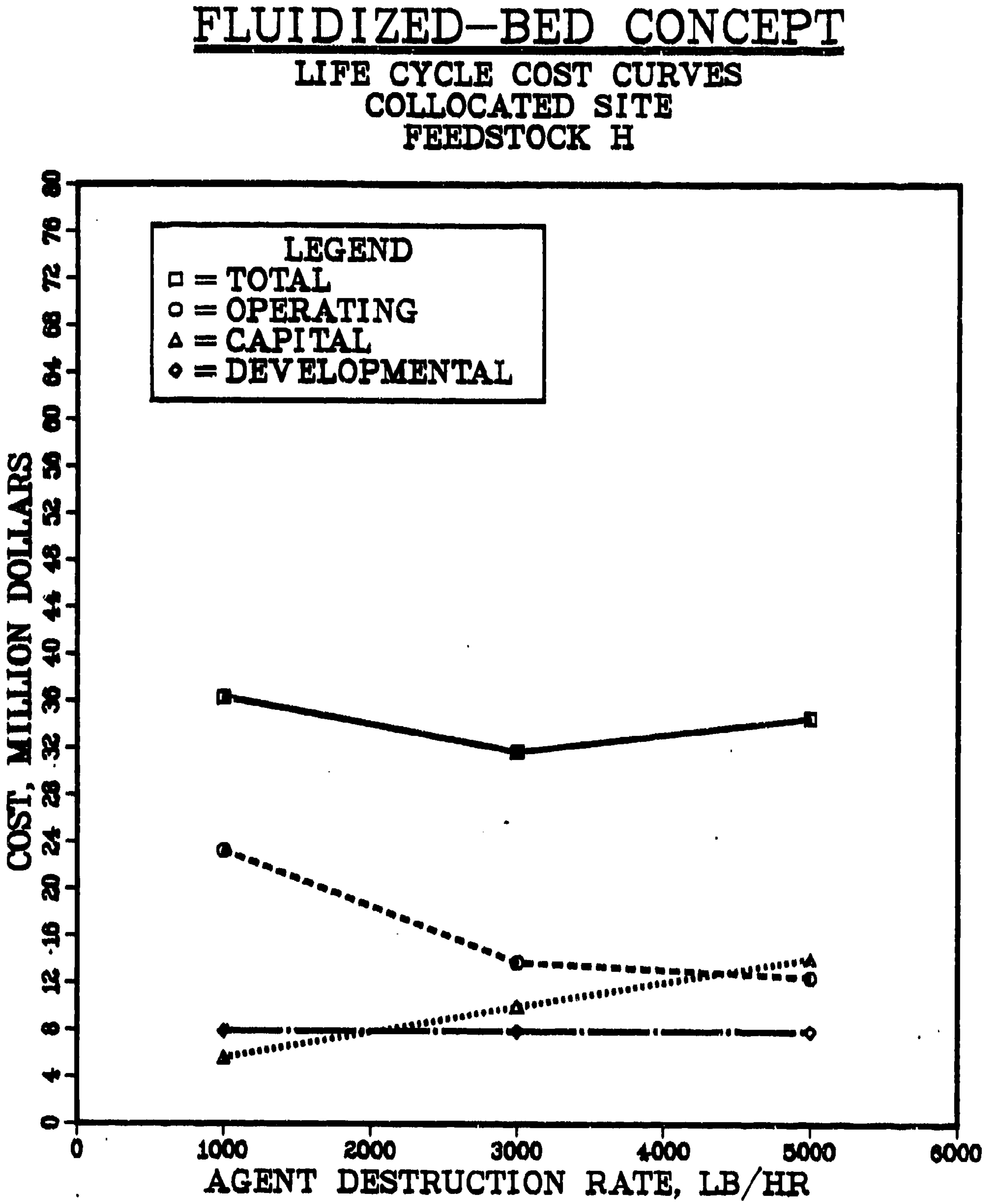

FLUIDIZED-BED CONCEPT
LIFE CYCLE COST CURVES
SINGLE SITE
FEEDSTOCK H
LEGEND
□ = TOTAL
○ = OPERATING
△ = CAPITAL
◇ = DEVELOPMENTAL
COST, MILLION DOLLARS
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
72
76
80
0
100
200
300
400
500
600
700
800
900
1000
1100
AGENT DESTRUCTION RATE, LB/HR

FIGURE G-8


FLUIDIZED-BED CONCEPT
LIFE CYCLE COST CURVES
COLLOCATED SITE
FEEDSTOCK H
LEGEND
□ = TOTAL
○ = OPERATING
△ = CAPITAL
◇ = DEVELOPMENTAL
COST, MILLION DOLLARS
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
72
76
80
0
1000
2000
3000
4000
5000
6000
AGENT DESTRUCTION RATE, LB/HR

## F. Optimum Process Flow Rate

The cost of the thermal process has a broad minimum of about \$16 million at about 400 lb/hr for a single site inventory and about \$32 million at about 3,000 lb/hr for a collocated site inventory. Since the minimum is not sharp, the optimum processing rate will certainly be affected and possibly governed by non-thermal considerations.

## G. Operating Time

The operating time for the various rates was presented in Table G-9. The optimum time for thermal processing is in the 3.5 to 4 year range. However, it should be noted that 1.84 years are assigned to scheduled downtime and thus the actual operating time is only about 2 years. Overheads not included in the thermal processing costs probably will make the optimum time somewhat less than indicated here.

APPENDIX H

ENGINEERING AND ECONOMIC ANALYSIS - IR VACUUM FURNACE

# APPENDIX H

## ENGINEERING AND ECONOMIC ANALYSIS - IR VACUUM FURNACE

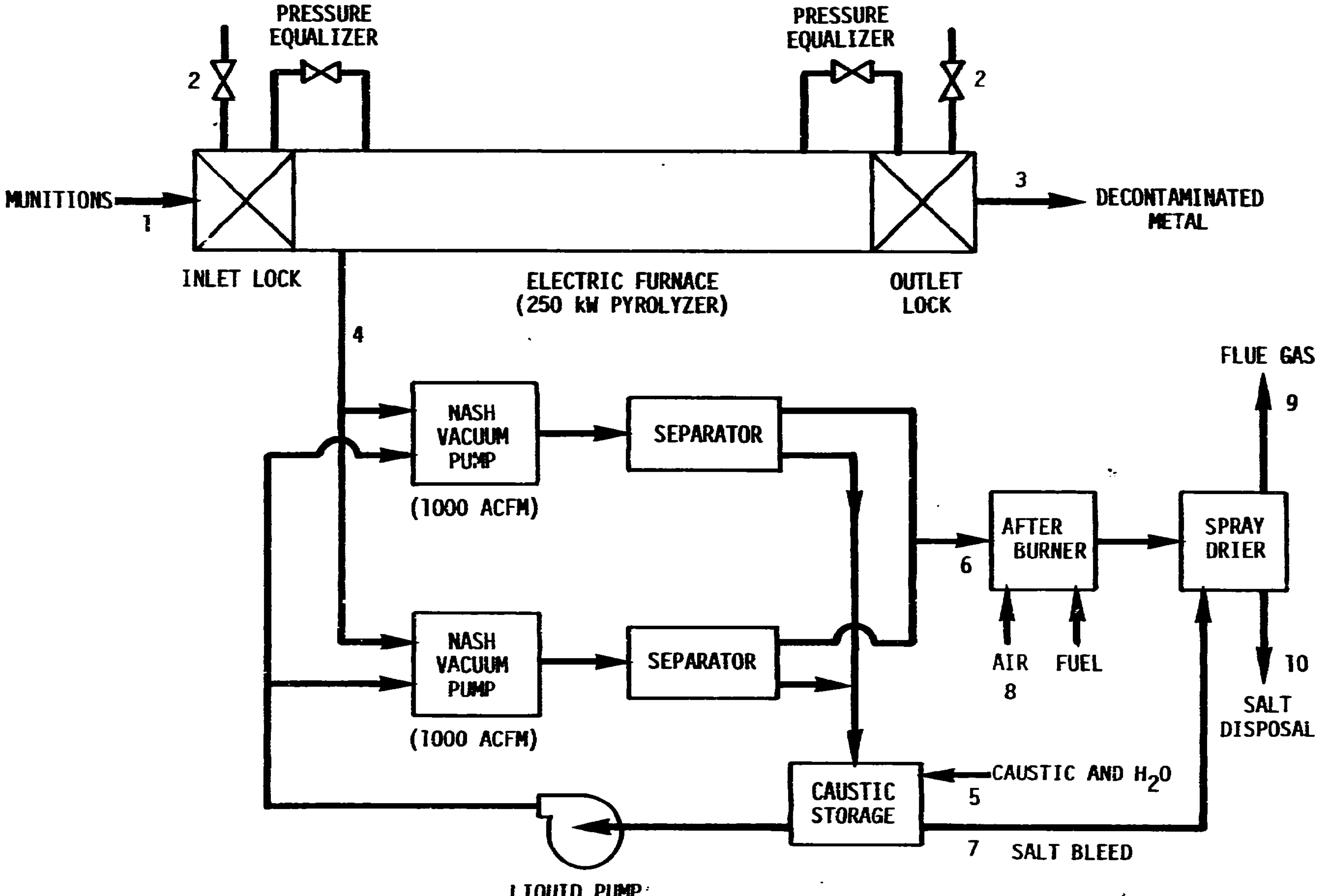
### Engineering Analysis

#### A. System Concept Description

The IR (Infrared) vacuum furnace concept was devised primarily as a method of minimizing downloading of explosives from the munitions. The deflagration to detonation transition is greatly reduced by vacuum operations. In this concept, munitions in configuration e, with agent and explosive cavities open and fuses and detonators removed, are placed on a tray and passed into a vacuum oven. The munition is heated and decontaminated. The agent pyrolyzes or evaporates, the propellants and explosives burn, and the metal is heated to the decontamination temperatue. Dunnage is heated and pyrolyzed.

Figure H-1 is a diagram of material flow through the vacuum furnace system. Before treatment, the munitions are downloaded to configuration c and placed on a tray. The tray is moved into the inlet lock (which is large enough to hold a spray tank). The lock is evacuated into the furnace, the furance door is opened, and the munition(s) is moved into the furance. The munition is heated, the agent is pyrolyzed or evaporated, and exhausted through a vacuum pump. Explosives deflagrate and the flue gas is exhausted through the vacuum pump. Dunnage is heated and pyrolyzed; the pyrolysis gases are exhausted through the vacuum pump. Solids leaving the furnace through the outlet lock have been heated to over 1000 F and therefore are decontaminated.

The vacuum pump acts as an effective scrubber for agent and acid gases. The caustic solution is cycled through the vacuum pump to absorb these gases.




NUMBERS REFER TO STREAMS IN HEAT AND MATERIAL BALANCE (TABLES H-1 AND H-2)

FIGURE H-1. VACUUM FURNACE (FEEDSTOCK "c")

The exhaust gas from the vacuum pump passes through an afterburner. The primary purpose of the afterburner is to burn the pyrolysis materials from the vacuum furnace. It will also act as a redundant system to assure that the agent is completely destroyed. The afterburner is a source of hot gas for the spray dryer.

The spray dryer acts to dry the salt solution bled from the vacuum pump. For costing, it is assumed to be the same as baseline. However, it should be simpler because in this concept the function of the spray dryer is to dry the salt rather than absorb acid gases.

Material and Energy Balance. Tables H-1 and H-2 present material and energy balances for a vacuum furnace system. The streams shown are keyed to Figure H-1. The energy losses shown were calculated by difference. These appear to be a little higher than would be expected. If the energy losses are, in fact, less than shown, the required temperature in the furnace could be maintained by reducing the electric heat, and the spray dryer temperature could be controlled by increasing the water to the salt system and therefore increasing the energy demand.

Design Parameters. Table H-3 is a list of the design parameters for the vacuum furnace system. A minimum of a 25-foot long furance is specified so that spray tanks can be treated. At the larger sizes, the unit is scaled up linearly to accommodate the larger throughput. The furnace would be in a vacuum chamber 8 feet in diameter. At the largest size, several parallel units might be used. However, this modification would not significantly alter costs.

The largest liquid seal vacuum pump has a capacity of about 1000 acfm. Smaller pumps were not considered because the pump must be sized for maximum flow rather than aveage flow, and with a small unit, individual munitions burning or pyrolyzing can substantially increase short-term flow rates over the average flow rate.

TABLE H-1. MATERIAL FLOW - IR VACUUM FURNACE SYSTEM
Basis 400 lb GB

| Stream* | Weight in lb | | | | | | | | | | Overall | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | In | Out |
| Material | | | | | | | | | | | | |
| GB | 400 | | | | | | | | | | 400 | |
| Wood | 650 | | | | | | | | | | 650 | |
| Explosive | 250 | | | | | | | | | | 250 | |
| Metal | 2,050 | | 2,050 | | | | | | | | 2,050 | 2,050 |
| Charcoal | | | 100 | | | | | | | | | 100 |
| Water liquid | | | | | 3,519 | | 3,600 | | | | 3,519 | |
| NaOH | | | | | 347 | | | | | | 347 | |
| $Na_2HPO_4$ | | | | | | | 406 | | | 406 | | 406 |
| NaF | | | | | | | 120 | | | 120 | | 120 |
| HF | | | | 57 | | | | | | | | |
| $P_2O_5$ | | | | 203 | | | | | | | | |
| CO | | | | 887 | | 887 | | | | | | |
| $H_2$ | | | | 61 | | 61 | | | | | | |
| $N_2$ | | 384 | | 427 | | 427 | | 8,019 | 8,446 | | 8,403 | 8,446 |
| $O_2$ | | 116 | | 0 | | 0 | | 2,436 | 1,218 | | 2,552 | 1,218 |
| $C_3H_6$ | | | | 65 | | 65 | | | | | | |
| $CO_2$ | | | | | | | | | 1,598 | | | 1,598 |
| $H_2O$ | | | | | | | | | 4,233 | | | 4,233 |
| TOTAL | 3,350 | 500 | 2,150 | 1,700 | 3,866 | 1,440 | 4,126 | 10,455 | 15,495 | 526 | 18,171 | 18,171 |

*Refer to Figure H-1.

TABLE H-2. ENERGY FLOW - IR VACUUM FURNACE SYSTEM
Basis 400 lb GB
$10^3$ Btu

| Stream* / Temperature F | 1 / 70 | 2 / 70 | 3 / 1000 | 4 / 1000 | 5 / 70 | 6 / 170 | 7 / 170 | 8 / 70 | 9 / 470 | 10 / 470 | Overall In | Overall Out |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| GB, heat of combustion | 4,000 | | | | | | | | | | 4,000 | |
| Wood, heat of combustion | 5,525 | | | | | | | | | | 5,525 | |
| Explosive, heat of combustion | 1,350 | | | | | | | | | | 1,350 | |
| Metal, sensible heat | 0 | | 380 | | | | | | | | | 380 |
| Charcoal, sensible heat | | | 50 | | | | | | | | | 50 |
| Charcoal, heat of combustion | | | 1,400 | | | | | | | | | 1,400 |
| Water, sensible heat | | | | | 0 | | 360 | | | | | |
| $Na_2HPO_4$, sensible heat | | | | | | | 20 | | | 80 | | 80 |
| NaF, sensible heat | | | | | | | 6 | | | 25 | | 25 |
| NaOH, sensible heat | | | | | 0 | | | | | | | |
| HF, sensible heat | | | | 20 | | | | | | | | |
| $P_2O_5$, latent and sensible heat | | | | 50 | | | | | | | | |
| CO, sensible heat | | | | 210 | | 21 | | | | | | |
| CO, heat of combustion | | | | 3,850 | | 3,850 | | | | | | |
| $H_2$, sensible heat | | | | 20 | | 2 | | | | | | |
| $H_2$, heat of combustion | | | | 3,720 | | 3,720 | | | | | | |
| $N_2$, sensible heat | | 0 | | 100 | | 10 | | 0 | 845 | | | 845 |
| $O_2$, sensible heat | | 0 | | | | | | 0 | 105 | | | 105 |
| $C_3H_6$, sensible heat | | | | 30 | | 3 | | | | | | |
| $C_3H_6$, heat of combustion | | | | 1,365 | | 1,365 | | | | | | |
| $CO_2$, sensible heat | | | | | | | | | 150 | | | 150 |
| $H_2O$, latent and sensible heat | | | | | | | | | 5,250 | | | 5,250 |
| Heat added | | | | 700 | | 525** | | | | | 1,225 | |
| Heat lost* (by difference) | | | | 380 | | 533 | | | 2,902 | | | 3815 |
| | | | | | | | | | | Total | 12,100 | 12,100 |

*Refer to Figure H-1.

**From energy to vacuum pump.

TABLE H-3. DESIGN PARAMETERS - IR VACUUM FURNACE

| | | | | | |
|---|---|---|---|---|---|
| Process Rate, lb/hr | 100 | 400 | 1000 | 3000 | 5000 |
| Furnace Size<br>Length/KW | 25/250 | 25/250 | 60/600 | 180/1800 | 300/3000 |
| Vacuum Pump, 1000 cpm<br>Number | 1 | 2 | 3 | 9 | 15 |
| Afterburner<br>Diam. x length, ft | 4 x 10 | 8 x 10 | 8 x 25 | 12 x 25 | 12 x 40 |

The afterburner is sized for 2 seconds residence time. This makes it adequate to assure agent destruction, although this function may not be necessary.

The spray dryer is assumed to be the same as baseline and was not resized.

B. System Feed Requirements

The vacuum furnace system is designed to accept feed configuration e. In feed configuration e, the agent and explosive cavities are open. Also, the fuses must be removed from the munitions and fed separately. The bursters themselves will still be in the munition. Under vacuum, without a fuse, the bursters should deflagrate rather than detonate. The agent cavity should also be open so that agent can escape from the munition without overpressurizing it. Rocket moters must be open so the rockets are not propelled in the furnace. The system is large enough to accommodate the large items. Trays will be used to hold the munitions as they pass through the furance.

C. Pollution Abatement Equipment

No special pollution abatement equipment is required. For cost purposes, the baseline equipment is assumed. This is probably slightly more costly than the equipment acutally needed because, in this concept, the spray dryer is used only for drying and not for acid gas absorption. However, the difference in cost should not be significant.

D. Ultimate Disposal

Disposal will be similar to baseline. A little less salt may be produced and some charcoal is expected from the wood dunnage. In general, the baseline costs used in this analysis are probably a

little higher than actual cost. After processing the munitions, the equipment probably will need a decon treatment before disposal or reuse.

## E. System Concept Advantages

The major advantage of the system is that explosions would not occur in the system, thus reducing the wear on the system. Another advantage is that only a minimum of downloading is necessary. Other important advantages are minimum caustic requirements and minimum salt generation.

Complete pollution control should be achieved in the vacuum pump and no further pollution control should be needed. Since no $CO_2$ is present at the vacuum pump, a minimum of caustic is needed. A spray dryer similar to that used in baseline will still be needed, but its function will be to dry salts rather than to scrub the flue gases.

## F. System Concept Disadvantages

The major disadvantage of the system is that many of the elements are new and require demonstration of feasibility. If some unproven assumptions are false, the entire system may be impractical. These include:

- Defused bursters in the munition will not detonate in vacuum.
- Pyrolysis tars will not interfere with the vacuum pump operation.
- The liquid residue, which may contain tars, can be dried satisfactorily in the spray dryer.

In addition, the system is fairly complicated in that many vacuum pumps are needed. Vacuum locks are needed to enter and remove items from the furnace.

## G. System Knowledge Gaps

As described in the disadvantages, this system has a number of untried processes. These knowledge gaps can be divided into two categories - fundamental assumptions and engineering data.

Fundamental Assumptions:

- No detonation in vacuum
- No agent in vacuum pump water
- No agent formed in drying
- No plugging of vacuum pump
- No plugging in vacuum pump liquid system.

Engineering Data:

- Treatment time of munitions and dunnage in vacuum
- Rate of decomposition of agent in vacuum
- Allowable salt concentration in vacuum pump water
- Combustion properties of gases from vacuum pump
- Evaporation properties of vacuum pump water.

## H. Safety

With the exceptions of the possibility of explosions occuring in spite of the vacuum or as a result of loss of vacuum, the system is inherently safe. The degree to which vacuum would supress explosions needs to be determined experimentally.

## I. Likelihood of Development in 5 Years.

If the system is practical, the development time should be about 5 years. A year or two is needed to demonstrate that the fundamental assumptions are correct. If they are proven reasonable, about another 2 or 3 years are needed to develop engineering data. The major elements in the system, vacuum pump, vacuum furnaces,

afterburners, and spray dryers are commercial equipment and therefore should not present major design or specification problems.

J. Scalability to 400-3,000 l/hr/Agent

The vacuum furnace can easily be made any size. The largest vacuum pumps available would be used and multiple units are necessary. Scale-down below 400 lb/hr is a minor problem in that the furnace must be large enough to treat a ton container or spray tank. A furnace of this size can treat about 400 lb/hr. Therefore, equipment cost savings is minimal below 400 lb/hr of agent.

K. Degree of Technical Risk

The possibility of vacuum suppressing an explosion of a burster in a munition has not been proven. However, detonations are in general suppressed by vacuum. The possibility of agent getting into the vacuum pump liquid is also substantial. Because of these factors, the technical risk is quite high. About 1 or 2 years of development work is necessary to prove possibility.

M. Material Capatibility Problems

There do not appear to be any significant material compatibility problems associated with this concept.

L. Ram Factors

Appendix L presents a list of the estimated amount of maintenance needed for the various parts of the system during normal operating hours. Maintenance during a normal shutdown or maintenance performed without shutdown is not included. From these estimates, the overall system is expected to have an availability of 0.885.

N. Energy Requirement and Source

The major energy requirement is the electric power for the volatilizer and the vacuum pump. A modest amount of fuel oil is needed for the afterburner for startup and standby. As shown previously in Table H-2, most of the energy required is supplied by burning munitions and dunnage. Table H-7 in the section on economics lists the cost of fuel and electricity for this process.

O. Ease of Operation

This should be an easy system to operate. The electric heaters would be controlled by an SCR controller; the vacuum pumps would operate wide open without control; the bleedstream from the water circulating system could be on an automatic batch control. The spray dry scrubber is used to dry salt rather than to absorb gases. The munition would be fed through the system on trays, and a tray-handling system to empty the trays and return them for refilling would be necessary. The major complication is the vacuum lock system for feeding and discharging munitions. Overall, the system is very simple.

## Economic Analysis

A. Facility Cost

Estimates of the facility and equipment costs are presented in Table H-4. The floor area of the facility is a Battelle estimate. The vacuum furnace is assumed to be in an explosion-resistant area, which is costed at $400/ft$^2$ while the other equipment is in a conventional room costed at $90/ft$^2$.

TABLE H-4. FACILITY AND EQUIPMENT COSTS - IR VACUUM FURNACE

| | Agent Feed Rate | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 100 lb/hr | | 400 lb/hr | | 1000 lb/hr | | 3000 lb/hr | | 5000 lb/hr | |
| | $ | $ft^2$ | $ | $ft^2$ | $ | $ft^2$ | $ | $ft^2$ | $ | $ft^2$ |
| **Facility Costs** | | | | | | | | | | |
| Vacuum Furnace at $400/$ft^2$ | 280,000 | 700 | 280,000 | 700 | 680,000 | 1,700 | 2,040,000 | 5,100 | 2,400,000 | 8,500 |
| Vacuum Pumps at $90/$ft^2$ | 9,000 | 100 | 14,000 | 150 | 18,000 | 200 | 54,000 | 600 | 90,000 | 1,000 |
| Dryer | 3,125 | 1,250 | 6,250 | 2,500 | 9,900 | 3,950 | 17,100 | 6,840 | 21,900 | 12,900 |
| Salt storage | 75,500 | 1,840 | 151,000 | 3,680 | 238,000 | 5,800 | 412,000 | 10,000 | 532,000 | 4,700 |
| Fuel tank fed | 1,650 | 660 | 3,300 | 1,320 | 5,250 | 2,100 | 9,090 | 3,640 | 11,700 | 4,700 |
| Afterburner | 36,000 | 400 | 54,000 | 600 | 90,000 | 1,000 | 160,000 | 2,000 | 270,000 | 3,000 |
| TOTAL | 406,000 | | 508,000 | | 1,041,000 | | 2,713,000 | | 4,326,000 | |
| **Equipment Cost** | | | | | | | | | | |
| Furnace, $ | 700,000 | | 700,000 | | 1,500,000 | | 3,600,000 | | 6,000,000 | |
| Vacuum shell - locks | 160,000 | | 160,000 | | 400,000 | | 1,200,000 | | 2,000,000 | |
| Vacuum pumps | 10,000 | | 20,000 | | 30,000 | | 90,000 | | 220,000 | |
| Spray dryer | 137,000 | | 295,000 | | 488,000 | | 893,000 | | 1,183,000 | |
| Forklift - truck | 71,000 | | 80,000 | | 155,000 | | 244,000 | | 716,000 | |
| Fuel tank | 18,000 | | 36,000 | | 72,000 | | 144,000 | | 180,000 | |
| Afterburner | 15,000 | | 35,000 | | 73,000 | | 115,000 | | 170,000 | |
| TOTAL | 1,111,000 | | 1,326,000 | | 2,718,000 | | 6,286,000 | | 10,469,000 | |
| Design at 25% | 380,000 | | 459,000 | | 940,000 | | 2,250,000 | | 3,699,000 | |
| TOTAL CAPITAL | 1,897,000 | | 2,293,000 | | 4,699,000 | | 11,249,000 | | 18,494,000 | |

## B. Capital Equipment

The furnace was estimated from an estimate of \$700,000 for a single furnace and \$500,000 for additional furnaces by a vendor (Salem Furnace Company) for a 4-foot x 4-foot x 25-foot, 250 KW electric furnace. That size furnace is adequate for 400 lb/hr; a smaller furnace can not be used at lower feed rates. Battelle estimated the sizes of the furnaces at the other rates (Table H-3) and costed th furnaces at \$200,000 + \$20,000/ft of length.

The vacuum shell was estimated to be 8 feet in diameter with 1/2-inch thick walls, and 50 feet longer than the furnace to allow for locks. The shell was estimated to cost \$1.37/lb from Peters and Timmerhaus (page 574).

The vacuum pump cost was supplied by a vendor (Nash) for a 1000 cfm unit made of cast iron. The number of units was estimated by Battelle. The dryer, salt storage, and fuel tanks were estimated from baseline costs. The actual dryer would be somewhat simpler than the baseline scrubber-dryer because it does not have to scrub acid gases. However, the cost savings should be minimal. The afterburner was costed at \$100 per square foot of surface area. Design cost was estimated at 25 percent of the facility and equipment cost.

## C. Operating Costs

The operating costs consist of labor costs, utility costs, and miscellaneous costs. An estimate of the labor required for the thermal part of the system is presented in Table H-5. Except for ultimate disposal, most of the manpower is used to monitor equipment and the manpower changes very little with rate.

The electric costs, which are a major part of the utility costs, are presented in Table H-6. The Battelle estimate of average power is shown along with the cost at \$0.05 per KWhr. Each vacuum pump is assumed to draw 75 KW. The caustic dryer is taken from baseline PB1 salt equipment cost.

TABLE H-5. LABOR REQUIREMENT - IR VACUUM FURNACE
(men/shift)

| | Agent Feed Rate, lb/hr | | | | |
|---|---|---|---|---|---|
| | 100 | 400 | 1000 | 3000 | 5000 |
| Furnace | 2 | 2 | 2 | 3 | 3 |
| Vacuum Pump | -- | -- | -- | -- | -- |
| Control Unit | 1 | 1 | 1 | 1 | 1 |
| Dryer | 1 | 1 | 2 | 2 | 2 |
| Ultimate Disposal | 2 | 4 | 6 | 8 | 8 |
| Maintenance | 2 | 2 | 2 | 3 | 3 |
| TOTAL/SHIFT | 8 | 10 | 13 | 17 | 17 |
| Man years/year | 24 | 30 | 39 | 51 | 51 |
| COST/YEAR, $ | 1,200,000 | 1,500,000 | 1,950,000 | 2,550,000 | 2,550,000 |

TABLE H-6. ELECTRIC COSTS - IR VACUUM FURNACE

| Agent Rate, lb/hr | 100 | 400 | 1000 | 3000 | 5000 |
|---|---|---|---|---|---|
| Furnace, KW used | 100 | 125 | 300 | 900 | 1,500 |
| $ for 6000 hr at $0.05/KW hr | 30,000 | 37,500 | 90,000 | 270,000 | 450,000 |
| Vacuum Pump, KW used | 75 | 150 | 225 | 675 | 1,125 |
| $ for 6000 hr at $0.05/KW hr | 22,500 | 45,000 | 67,000 | 202,500 | 338,000 |
| Caustic Dryer, KW used | 50 | 100 | 150 | 200 | 300 |
| $ for 6000 hr at $0.05/KW hr | 15,000 | 30,000 | 45,000 | 60,000 | 90,000 |
| TOTAL | 67,500 | 112,500 | 202,500 | 532,500 | 878,000 |

Other non-labor operating costs are presented in Table H-7. The water cost is nominal and taken from baseline. The fuel cost is for 1000 hours of operation of the afterburner on standby. No fuel is required for operation. Spare parts and supplies are taken as a percentage of capital or other operating costss as in the baseline.

The life cycle operating costs are presented in Table H-8. Equipment, training, changeout and shutdown times are taken from baseline. The operating times assume an availability of 0.865 and 5,000 hours per year of scheduled operating time.

## D. Development Cost

An estimate of the development costs is presented in Table H-9.

## E. Total Costs

The total life cycle costs are presented in Table H-10 and Figures H-3 and H-4. Costs range from $17 million for single site to $36 million for collocation.

## F. Optimum Process Flow Rate

The lowest point on the curves are for operating at 400 lb/hr for the single site or 3000 lb/hr for a collocated site. Except for high costs for operating at 100 lb/hr, the costs are not particularly sensitive to operating rate, and the costs for other parts of the system may change the optimum operating rate.

## G. Operating Cost

Operating times for the disposal of various agent categories are given in Table H-8.

## TABLE H-7. OPERATING COST - IR VACUUM FURNACE
(Annual Usage/Cost, $)

| | Agent Feed Rate, lb/hr | | | | |
|---|---|---|---|---|---|
| | 100 | 400 | 1000 | 3000 | 5000 |
| Water (baseline) | | | | | |
| $10^6$ gal/year | 6 | 12 | 19 | 31 | 40 |
| Cost, $/year | 3,180 | 6,360 | 10,000 | 16,500 | 21,000 |
| Electric, $/year | 67,500 | 112,500 | 202,500 | 532,500 | 878,000 |
| Fuel, $/year | 12,000 | 48,000 | 120,000 | 360,000 | 600,000 |
| Total Utilities | 83,000 | 167,000 | 333,000 | 909,000 | 1,499,000 |
| Spare parts 6% Capital, $/year | 114,000 | 138,000 | 282,000 | 675,000 | 1,110,000 |
| Materials 10% Other Operating, $/year | 140,000 | 181,000 | 257,000 | 413,000 | 516,000 |
| TOTAL NONLABOR OPERATING COST, $/year | 337,000 | 486,000 | 872,000 | 1,997,000 | 3,125,000 |

TABLE H-8. LIFE CYCLE OPERATING COSTS - IR VACUUM FURNACE

| Agent Rate, lb/hr | 100 lb/hr, Single Site | | | | 400 lb/hr, Single Site | | | | 1000 lb/hr, Single Site | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Duration year | Annual Labor Cost, $/yr | Other Annual Cost, $/yr | Total Cost, $ | Duration, year | Annual Labor Cost, $/yr | Other Annual Cost, $/yr | Total Cost, $ | Duration, year | Annual Labor Cost, $/yr | Other Annual Cost, $/yr | Total Cost, $ |
| Equipment Acceptance | 0.5 | 400,000 | 112,000 | 256,000 | 0.5 | 500,000 | 162,000 | 331,000 | 0.5 | 650,000 | 291,000 | 471,000 |
| Training | 0.5 | 1,200,000 | 169,000 | 685,000 | 0.5 | 1,500,000 | 243,000 | 872,000 | 0.5 | 1,950,000 | 436,000 | 1,193,000 |
| Operation - Miners and rockets | 2.48 | 1,200,000 | 337,000 | 382,000 | 0.61 | 1,500,000 | 486,000 | 1,212,000 | 0.25 | 1,950,000 | 872,000 | 705,000 |
| Chargeout | 0.17 | 1,200,000 | 169,000 | 233,000 | 0.17 | 1,500,000 | 243,000 | 296,000 | 0.17 | 1,950,000 | 436,000 | 406,000 |
| Operation - Projectiles | 3.3 | 1,200,000 | 337,000 | 5,072,000 | 0.82 | 1,500,000 | 486,000 | 1,629,000 | 0.33 | 1,950,000 | 872,000 | 931,000 |
| Chargeout | 0.17 | 1,200,000 | 169,000 | 233,000 | 0.17 | 1,500,000 | 243,000 | 296,000 | 0.17 | 1,950,000 | 436,000 | 406,000 |
| Operation - Bulk items | 1.1 | 1,200,000 | 337,000 | 1,691,000 | 0.28 | 1,500,000 | 486,000 | 556,000 | 0.11 | 1,950,000 | 872,000 | 310,000 |
| Shutdown | 0.5 | 400,000 | 112,000 | 256,000 | 0.5 | 500,000 | 162,000 | 331,000 | 0.5 | 650,000 | 291,000 | 470,000 |
| TOTAL | 8.72 | | | 12,238,000 | 3.55 | | | 5,522,000 | 2.53 | | | 4,892,000 |

TABLE H-8, continued

| Agent Rate, lb/hr | 1000 lb/yr, Collocated | | | | 3000 lb/yr, Collocated | | | | 5000 lb/yr, Collocated | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Duration year | Annual Labor Cost, $/yr | Other Annual Cost, $/yr | Total Cost, $ | Duration, year | Annual Labor Cost, $/yr | Other Annual Cost, $/yr | Total Cost, $ | Duration, year | Annual Labor Cost, $/yr | Other Annual Cost, $/yr | Total Cost, $ |
| Equipment Acceptance | 0.5 | 650,000 | 291,000 | 471,000 | 0.5 | 850,000 | 660,000 | 758,000 | 0.5 | 850,000 | 1,042,000 | 946,000 |
| Training | 0.5 | 1,950,000 | 436,000 | 1,193,000 | 0.5 | 2,550,000 | 990,000 | 1,775,000 | 0.5 | 2,550,000 | 1,563,000 | 2,056,000 |
| Operation - Miners and rockets | 2.48 | 1,950,000 | 872,000 | 6,999,000 | 0.83 | 2,550,000 | 1,997,000 | 3,774,000 | 0.5 | 2,550,000 | 3,125,000 | 2,838,000 |
| Chargeout | 0.17 | 1,950,000 | 436,000 | 406,000 | 0.17 | 2,550,000 | 1,563,000 | 699,000 | 0.17 | 2,550,000 | 1,563,000 | 699,000 |
| Operation - Projectiles | 3.3 | 1,950,000 | 872,000 | 9,313,000 | 1.1 | 2,550,000 | 1,997,000 | 5,002,000 | 0.67 | 2,550,000 | 3,125,000 | 3,802,000 |
| Chargeout | 0.17 | 1,950,000 | 436,000 | 406,000 | 0.17 | 2,550,000 | 999,000 | 603,000 | 0.17 | 2,550,000 | 1,563,000 | 699,000 |
| Operation - Bulk items | 1.1 | 1,950,000 | 872,000 | 3,104,000 | 0.37 | 2,550,000 | 1,997,000 | 1,682,000 | 0.22 | 2,550,000 | 3,125,000 | 1,259,000 |
| Shutdown | 0.5 | 650,000 | 291,000 | 470,000 | 0.5 | 850,000 | 666,000 | 758,000 | 0.5 | 850,000 | 1,042,000 | 946,000 |
| TOTAL | 8.72 | | | 4,892,000 | 4.14 | | | 14,955,000 | 3,23 | | | 13,236,000 |

TABLE H-9. DEVELOPMENT COSTS - IR VACUUM FURNACE

| | |
|---|---|
| Lab Scale Program | |
| Labor & Fee | 600,000 |
| Materials | 150,000 |
| Subcontractors | 150,000 |
| Contingencies | 60,000 |
| Total Lab Scale | 960,000 |
| Pilot Plant Test Program | |
| Conceptual Design | 250,000 |
| Test Plan | 40,000 |
| Pilot Plant | |
| Construction | 1,897,000 |
| Startup and Training | 941,000 |
| Operation 1 year | 1,537,000 |
| Process Development | 3,700,000 |
| Subtotal Pilot Plant | 8,365,000 |
| TOTAL DEVELOPMENT | 9,325,000 |

TABLE H-10. COST SUMMARY - IR VACUUM FURNACE

| | Single Site | | | Collected | | |
|---|---|---|---|---|---|---|
| Rate, lb/hr | 100 | 400 | 1000 | 1000 | 3000 | 5000 |
| Capital, $ | 1,897,000 | 2,293,000 | 4,699,000 | 4,699,000 | 11,249,000 | 18,494,000 |
| Operating, $ | 12,237,000 | 5,522,000 | 4,892,000 | 22,361,000 | 14,955,000 | 13,235,000 |
| Development, $ | 9,325,000 | 9,325,000 | 9,325,000 | 9,325,000 | 9,325,000 | 9,325,000 |
| TOTAL | 23,459,000 | 17,140,000 | 18,916,000 | 36,385,000 | 35,529,000 | 41,054,000 |

FIGURE H-3

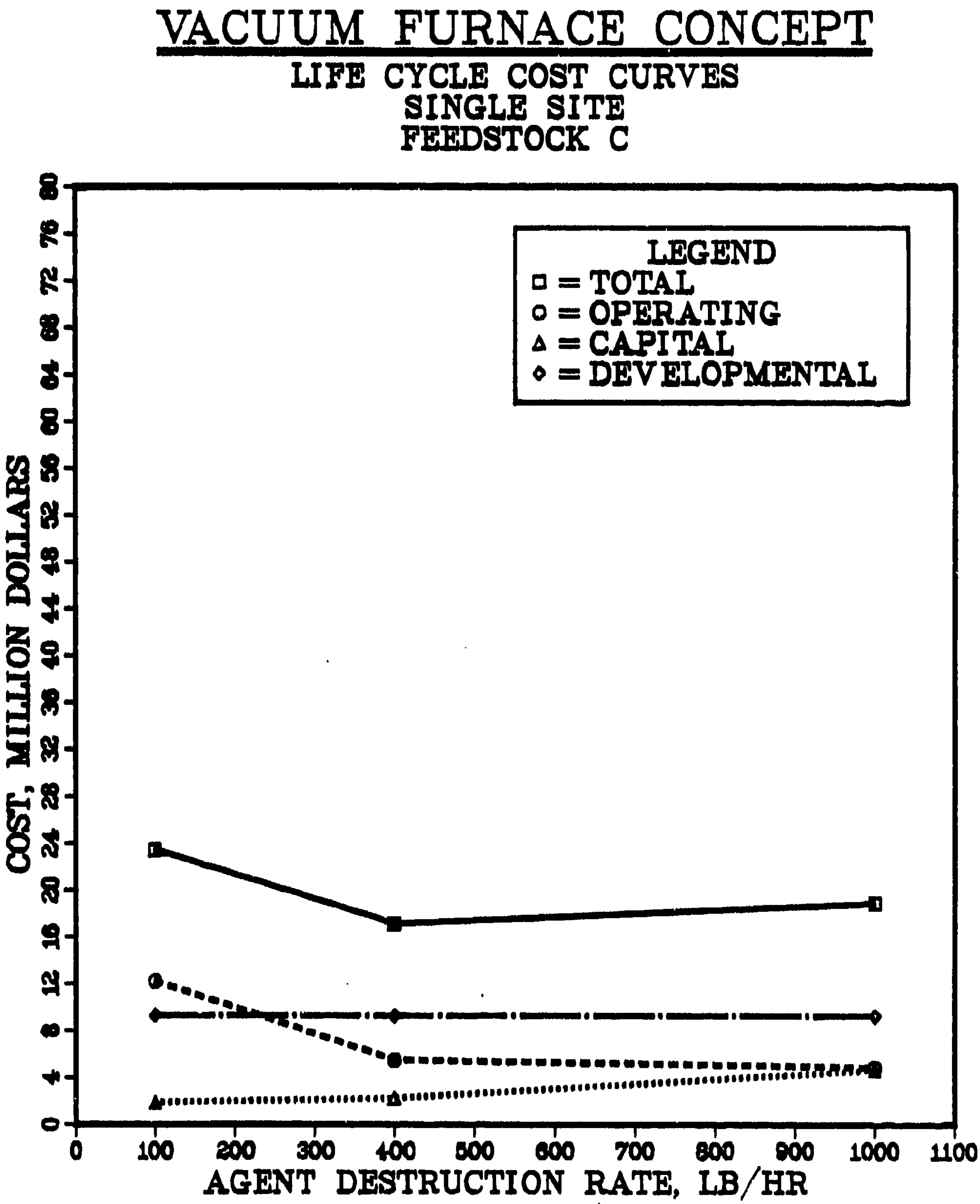
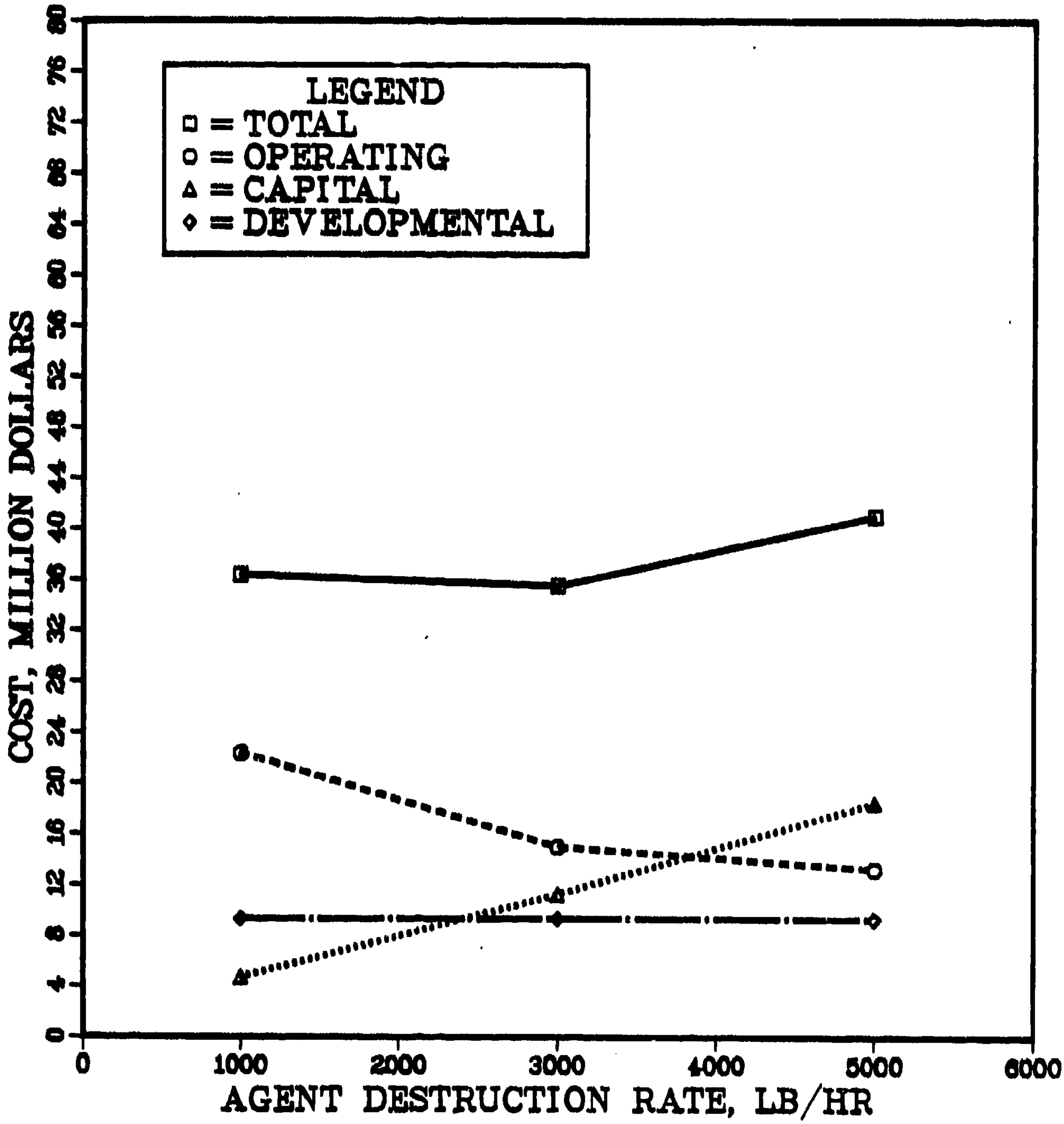

VACUUM FURNACE CONCEPT
LIFE CYCLE COST CURVES
SINGLE SITE
FEEDSTOCK C
LEGEND
□ = TOTAL
○ = OPERATING
△ = CAPITAL
◇ = DEVELOPMENTAL
COST, MILLION DOLLARS
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
72
76
80
0
100
200
300
400
500
600
700
800
900
1000
1100
AGENT DESTRUCTION RATE, LB/HR

FIGURE H-4

# VACUUM FURNACE CONCEPT

## LIFE CYCLE COST CURVES
## COLLOCATED SITE
## FEEDSTOCK C



APPENDIX I

ENGINEERING AND ECONOMIC ANALYSIS - SHAFT FURNACE

# APPENDIX I

## ENGINEERING AND ECONOMIC ANALYSIS - SHAFT FURANCE

### Engineering Analysis

#### A. System Concept Description

The shaft furnace system is proposed to handle feedstocks b and c. All items, including munitions with bursters comprised of up to 8 pounds of explosive and excluding rockets, ton containers, spray tanks, and bombs are fed to the system without special preparations. The system is illustrated in Figure I-1 and mass and heat balances are presented in Tables I-1 and I-2.

Items are dropped into the furance via a lock formed by two valves at the top of the furnace and fall into a bed of hot scrap metal (900 F) that is recycled continuously. The recycling scrap covers the munition and transfers to it the heat required to elevate its temperature to the point at which the explosive will detonate or the agent will burst open the cavity. The scrap also serves to prevent munition fragments from reaching the walls of the reactor and, while doing so, reduces the energy generated by a detonation. The released agent is combusted in the furnace and passes through an air pollution control system of baseline design (spray dry scrubber and baghouse). The metal parts pass with the scrap bed out through the bottom of the furnace first to screens, where oversized and undersized scrap are removed, and then on to bucket elevators which recycle the scrap to the top of the furnace. The screens and bucket elevator are enclosed and form a sealed unit with the furnace.

A scrap metal bed with a diameter of 20 ft is assumed to be sufficient to protect the walls of the furnace. The height of the shaft is determined by the process rate and time required for munition explosions. Munitions are fed so that the scrap between them measures

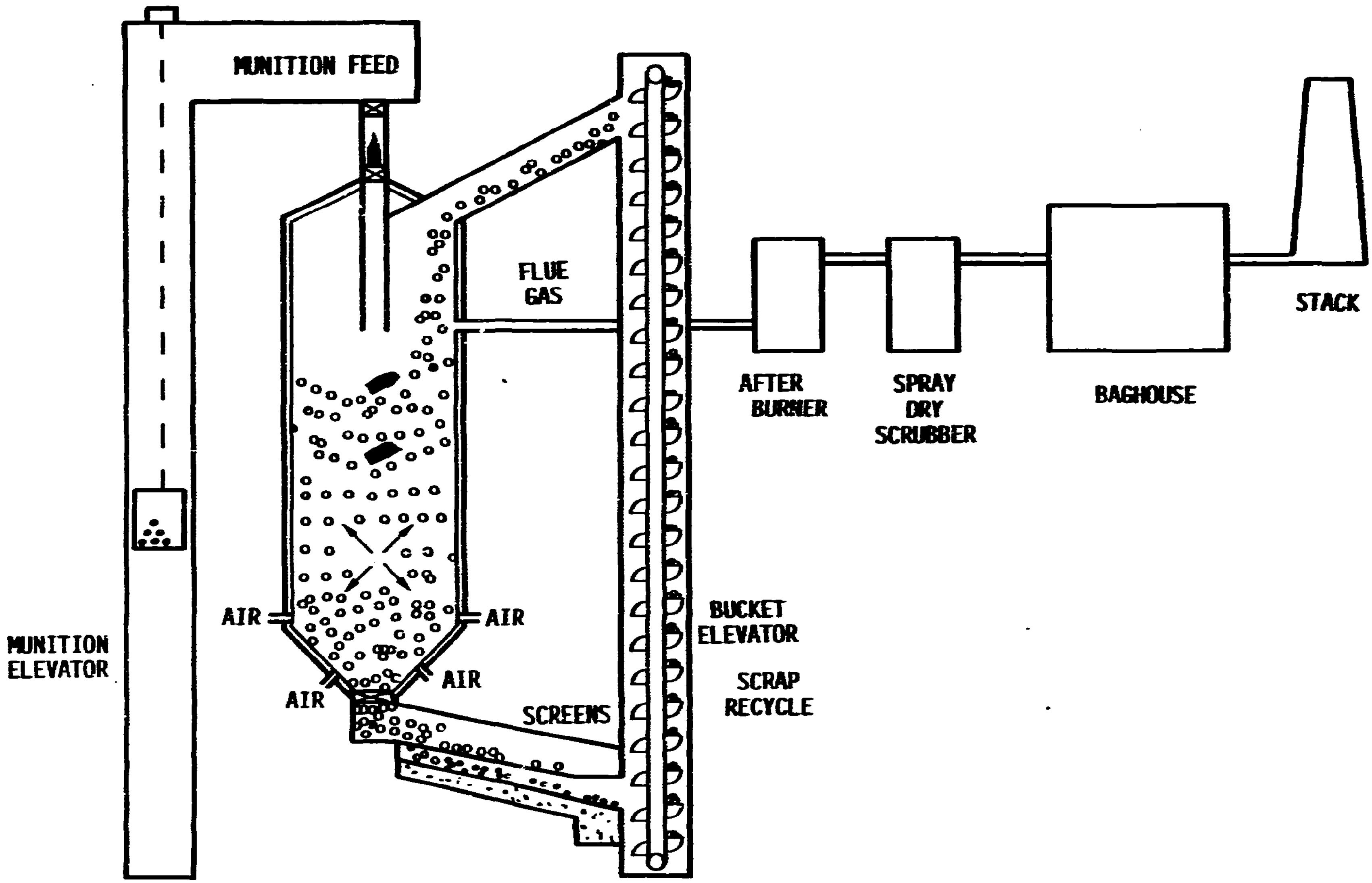



FIGURE I-1. SHAFT FURNACE

TABLE I-1. MATERIAL BALANCE SHAFT FURNACE (400 lb/hr Agent Feed Rate)

| Material | lb/hr |
| --- | --- |
| **IN** | |
| GB | 400 |
| Explosive-Propellant | 250 |
| Wood | 650 |
| Metal | 2,050 |
| Fuel Oil | 274 |
| Air | 30,452 |
| Water | 8,547 |
| NaOH | 572 |
| TOTAL | 43,195 |
| **OUT** | |
| Flue Gas | 40,316 |
| Salts | 829 |
| Metal | 2,050 |
| TOTAL | 43,195 |

TABLE I-2. HEAT BALANCE SHAFT FURNACE

| Material | Heat of Combustion (Btu/lb) | Temperature, (f) | H, (Btu) |
|---|---|---|---|
| | **IN** | | |
| GB | 10,073 | 70 | 4,029,200 |
| Explosive-Propellant | 5,400 | 70 | 1,350,000 |
| Wood | 8,500 | 70 | 5,525,000 |
| Metal | --- | 70 | --- |
| Fuel Oil | 19,695 | 70 | 5,396,394 |
| Air | --- | 70 | --- |
| Water | --- | 70 | --- |
| NaOH | --- | 70 | --- |
| TOTAL | | | 16,271,000 |
| | **OUT** | | |
| Flue Gas | | 300 | 11,886,264 |
| Salts | | 300 | 47,668 |
| Metal | | 900 | 204,180 |
| Heat Losses (by difference) | | | 4,162,483 |
| TOTAL | | | 16,300,594 |

NOTE: Heat of reaction to form salts from NaOH and acids neglected.

at least three times the diameter of the munition. The distance between the munitions is assumed to prevent a chain reaction of explosions in the bed. The time required for munition detonation is assumed to be the time required to raise the temperature of the metal casing and agent to 300 C. Design parameters such as bed height, bed velocity, recycle rate, and explosion time for 105 mm projectes at an agent processing rate of 400 lb/hr are given in Table I-3. A bed height of 65 ft is taken to be the upper limit. At greater heights, required for higher throughputs, the recycle rates become impractical. As a result, multiple units are required for higher agent processing rates.

A metal parts furnace or heated discharge conveyor must also be used while processing some munitions since 5X decontamination within the furnace itself would require impractical bed heights for those munitions.

## B. System Feed Requirements

The shaft furnace is assumed to be capable of handling whole items containing up to 8 pounds of explosive (feedstock b). Rockets must be made nonpropulsive and ton containers, spray tanks, and bombs must be punched to prevent large gas surges and the production of large, irregular metal pieces resulting from bursting of the thin-walled containers (feedstock c).

## C. Pollution Abatement System

The baseline pollution abatement system will be used. This will consist of a spray dry scrubber followed by a baghouse, induced draft fan and stack.

## D. Ultimate Disposal

The ultimate disposal scenario will be similar to that of the baseline. The dried salts from the spray dryer scrubber and the

TABLE I-3. DESIGN PARAMETERS SHAFT FURNACE (400 lb/hr Agent Destruction Rate 105 mm Projectiles)

| | |
|---|---|
| Furnace Diameter | 20 ft |
| Munitions/hr | 250 |
| Detonation Time | .16 hr (9.6 minutes) |
| Distance Between Munition | 1.4 |
| Bed Depth Required for Processing Rate | 66 ft (50 ft + 10 ft clearance at bottom of furance) |
| Scrap Recycle Rate | 350 ft/hr<br>13,205 tons/hr<br>(assuming steel scrap, .5 void fraction) |
| Furnace Operating Temperature | 900 F |
| Excess Air Requirement | 285 percent |
| Afterburner Operating Temperature | 1600 F |
| Gas Residence Time (Afterburner) | 2 seconds |

particulates captured in the baghouse will be drummed and stored as at CAMDS. Decontaminated metal parts and bed can be sold as scrap. Wood ash not carried from the dunnage incinerator can be landfilled.

## E. System Concept Advantages

Advantages of the concept include:

- Ability to handle detonable items
- Low requirement for supplemental fuel and tolerance of short term irregularities in fuel feed rates due to large thermal inertia of the scrap bed
- Fewer problems handling aluminum rockets due to low operating temperature.

## F. System Concept Disadvantages

Disadvantages of the concept are:

- High degree of technical risk
- Must operate at low temperatures
- Large recycle rates
- Metal will not always be 5X decontaminated within the shaft furnace.

## G. System Concept Knowledge Gap

The most important knowledge gap associated with the process is whether the scrap bed can attenuate the blast wave and, if so, what size bed is required. The behaviour of the detonable items and times required for explosion or for the agent to burst the cavity are also unknown.

It may be noted that the diameter of the shaft has been chosen somewhat arbitrarily. Should tests indicate that a smaller diameter is satisfactory, process feasibility will be enhanced.

## H. Safety

Several knowledge gaps must be resolved before the safety of the system can be determined. The primary concern is the ability of the scrap bed to reduce fragment velocities and attenuate the blast energy thus avoiding destruction of the reactor. Also, blast wave and/or gas surges must be attenuated in the duct leading to the afterburner.

## I. Likelihood of Development Within 5 Years

The development of the shaft furnace would require extended bench and pilot-scale studies. The concept, although originally thought to be developable within 5 years, is now expected to require more than 5 years.

## J. Scalability

Due to the large recycle rates and bed heights required for the concept, a single unit would not be capable of handling agent feed rates much in excess of 400 lb/hr. Multiple units are required at the higher feed rates.

## K. Degree of Technical Risk

A high degree of technical risk is associated with the process since the degree with which large, continual detonations can be contained successfully is unproven.

## L. RAM Factors

Performance information on equipment of this type was not available. Based on engineering judgement and experience in developing system availability factors for other processes, system availability for the shaft furnace was estimated at 0.8.

## M. Materials Compatability Problems

The major corrosion problem (due to the high temperature) will occur in the afterburner. This problem is common with the baseline process and thus can be considered resolved. Reaction of the halogens and phosphorous with the scrap may occur, causing the discharged scrap to be contaminated with these elements. This potential problem must be examined.

## N. Energy Requirement and Source

The two major energy requirements are for fuel and electricity. Although additional fuel is not required in the furnace during ordinary operation, fuel is needed to operate the afterburner at the required temperature and to raise the temperature of scrap bed after shutdowns. The primary electrical requirement is for running the scrap conveyors (300 Hp motors).

## O. Ease of Operation

The system may be difficult to operate due to problems associated to the large recycle rate requirement involving irregular scrap. Because the process releases agent in surges, the feed system locks must seal well and this may be troublesome. The shaft discharge mechanism, double screen and discharge lock appear to be potentially troublesome areas that are difficult to repair in event of failure or jamming.

## Economic Analysis - Shaft Furnace

## A. Facility Cost

The facility costs are presented in Tables I-4 and I-5. The main building includes the furnace, afterburner, conveyors, munition

TABLE I-4. SINGLE SITE FACILITY COSTS
SHAFT FURNACE

| Agent Rate | 100 lb/hr (1 unit) | 400 lb/hr (1 unit) | 1000 lb/hr (3 units) |
|---|---|---|---|
| Main Building | $1,560,000 | $1,560,000 | $4,680,000 |
| APC Pad | $ 2,720 | $ 6,250 | $ 8,496 |
| Salt and Drum Storage | $ 65,674 | $ 150,880 | $ 205,511 |
| Fuel Tank Pad | $ 1,650 | $ 3,300 | $ 9,013 |
| TOTAL | $1,630,000 | $1,720,430 | $4,903,020 |

TABLE I-5. COLLOCATE SITE FACILITY COSTS
SHAFT FURNACE

| Agent Rate | 1000 lb/hr (3 units) | 3000 lb/hr (8 units) | 5000 lb/hr (13 units) |
|---|---|---|---|
| Main Building | $4,680,000 | $12,500,000 | $20,300,000 |
| APC Pad | $ 8,496 | $ 16,425 | $ 22,316 |
| Salt and Drum Storage | $ 205,511 | $ 397,290 | $ 539,780 |
| Fuel Tank Pad | $ 9,013 | $ 24,766 | $ 48,440 |
| TOTAL | $4,903,020 | $12,938,481 | $20,910,563 |

elevator, and screens. The cost was calculated at $400/ft$^2$. The APC Pad (spray dry scrubber and drumming), Salt and Storage, and Fuel Tank Pad were calculated by scaling from the Baseline Drum.

B. Equipment Costs

The capital equipment costs are listed in Tables I-6 and I-7. The furnace cost was calculated on a weight basis using a formula for pressure vessels (Peters and Timmerhaus, 1980). The installation cost (80 percent) was estimated. Due to the size of the vessel (20 ft x 75 ft) field erection would probably be required. The afterburner costs were scaled using the six-tenths-factor rule (Peters and Timmerhaus, 1980) on a volume basis of 329 ft$^3$ for $99,915 (verbal quote from Brulé). The 40 percent installation charge was estimated.

The scrap conveyors were costed using a quote from the Jervis B. Webb Co. for a single conveyor with a 2500 ton/hr capacity (300 Hp motors) for $140,000/conveyor and $560,000/conveyor for conveying the steel scrap at temperatures near 900 F. The 84 percent installation charge was taken from "Capital Cost Estimating" (Gutherie, 1969). The costs of the munition elevator and screens were also taken from the Gutherie reference.

The screen costs were based on the area required for screening. The screening area was estimated using the following approximation for vibrating screens

$$\text{Capacity (tons/hour-ft}^2\text{-mm screen opening)} = .2-.8$$
(McCabe and Smith, 1976)

The scrap metal cost was estimated using prices listed in Iron Age and discussions with vendors as guidelines. The estimate may be low since the scrap used in the system is assumed to be spherically shaped to facilitate handling (screening and conveying).

TABLE I-6. SINGLE SITE EQUIPMENT COSTS
SHAFT FURNACE

| Agent Rate | 100 lb/hr (1 unit) | 400 lb/hr (1 unit) | 1000 lb/hr (3 units) |
|---|---|---|---|
| Furnace (80% installation) | $ 257,000 | 407,264 | 1,222,793 |
| After Burner (40% installation) | $ 103,144 | 236,781 | 710,342 |
| Scrap Conveyor (80% installation) | $3,024,000 | 6,048,000 | 14,112,000 |
| Munition Elevator | $ 38,242 | 49,168 | 147,506 |
| Screens (30% installation) | $ 158,600 | 234,372 | 703,300 |
| Scrap | $ 92,128 | 250,000 | 750,000 |
| Locks (25% installation) | $ 15,000 | 15,000 | 45,000 |
| Air Heat Exchanger | $ 50,238 | 115,000 | 200,000 |
| Residue Handling Track | $ 65,790 | 65,790 | 130,000 |
| Storage Forklift | $ 22,000 | 22,000 | 44,000 |
| Scrubber and Baghouse | $ 292,092 | 671,050 | 1,194,201 |
| Subtotal | $4,118,234 | 8,114,425 | 19,259,142 |
| Design | 20% | 20% | 20% |
| Total Equipment | $4,941,880 | 9,737,310 | 23,110,970 |
| Total Capital | $6,572,880 | 11,457,774 | 28,013,990 |

TABLE I-7. COLLOCATED EQUIPMENT COSTS
SHAFT FURNACE

| Agent Rate | 1000 (3 units) | 3000 (8 units) | 5000 (13 units) |
|---|---|---|---|
| Furnace (80$ installation) | $ 1,221,793 | 3,258,112 | 5,294,443 |
| Afterburner (40% installation) | $ 710,342 | 1,894,248 | 3,078,153 |
| Scrap Conveyor (80% installation) | $14,112,000 | 48,838,400 | 78,642,000 |
| Munition Elevator | $ 147,506 | 393,350 | 639,184 |
| Screens (30% installation) | $ 903,300 | 1,874,600 | 3,047,200 |
| Scrap | $ 750,000 | 1,880,000 | 3,750,000 |
| Locks (25% installation) | $ 45,000 | 120,000 | 195,000 |
| Air Heat Exchanger | $ 200,000 | 386,636 | 525,000 |
| Residue Handling Truck | $ 130,000 | 195,000 | 650,000 |
| Storage Forklift | $ 44,000 | 44,000 | 44,000 |
| Scrubber and Baghouse | $ 1,194,201 | 2,308,609 | 3,137,604 |
| Subtotal | $19,259,142 | 61,192,955 | 98,985,584 |
| Design | 20% | 20% | 20% |
| Total Equipment | $23,110,970 | 73,432,546 | 118,782,000 |
| Total Capital | $28,013,990 | 86,371,027 | 139,692,540 |

The costs of the air heat exchanger, residue handling track, storage forklift, scrubber, and baghouse were determined by scaling from the baseline costs.

## C. Operating Costs

The personnel requirements and costs for the single and collocated systems are presented in Tables I-8 and I-9. The requirements are estimates obtained using the baseline as a guideline.

The non-labor operating costs are listed in Table I-10 and I-11. The water and electrical (air heat exchanger, scrubber, salt equipment) requirements and costs were calculated by adjusting or scaling from the baseline. The major electrical expense was for running the conveyor motors (300 Hp each). The fuel is required to operate the afterburner at 1600 F.

The total life operating costs are listed in Tables I-12 and I-13 and inlcude both labor and nonlabor (labelled other direct) costs. Changeout periods were assumed to not be necessary since rockets, ton containers, and bombs could be processed first with similar preparations. Also, the furnace is not lined with a refractory.

## D. Development Cost

The development costs are presented in Table I-14.

## E. Total Cost

The total costs for single and collocated sites are presented in Table I-15. The life cycle cost curves for the single and collocated systems are presented in Figures I-2 and I-3.

TABLE I-8. SINGLE SITE LABOR COSTS
SHAFT FURNACE

| Agent Rate | Personnel Requirements 100 lb/hr (1 unit) | 400 lb/hr (1 unit) | 1000 lb/hr (3 units) |
|---|---|---|---|
| Control Room | 1 | 1 | 2 |
| Munition Feed | 1 | 1 | 3 |
| Ultimate Disposal | 2 | 4 | 6 |
| Maintenance | 2 | 4 | 6 |
| Pollution Abatement | 1 | 1 | 2 |
| Total/Shift | 7 | 9 | 17 |
| Shift | X 3 | X 3 | X 3 |
| Man Years/Year | 15 | 27 | 51 |
| Rate ($50,000/Yr) | X 50 | X 50 | X 50 |
| Labor Cost/Year | $750,000 | 1,350,000 | 2,550,000 |

TABLE I-9. COLLOCATED LABOR COSTS
SHAFT FURNACE

| Agent Rate | Personnel Requirements 1000 lb/hr (3 units) | 3000 lb/hr (8 units) | 5000 lb/hr (13 units) |
|---|---|---|---|
| Control Room | 2 | 3 | 5 |
| Munition Feed | 3 | 8 | 13 |
| Ultimate Disposal | 6 | 10 | 14 |
| Maintenance | | 8 | 13 |
| | 2 | 3 | 4 |
| Total/Shift | 17 | 32 | 49 |
| Shifts | X 3 | X 3 | X 3 |
| Man Years/Year | 51 | 96 | 137 |
| Rate ($50,000/Yr) | X 50 | X 50 | X 50 |
| Labor Cost/Year | $2,550,000 | 4,800,000 | 6,850,000 |

TABLE I-10. SINGLE SITE OPERATING COSTS
SHAFT FURNACE

| Agent Rate | 100 lb/hr (1 unit) | 400 lb/hr (3 units) | 1000 lb/hr (8 units) |
|---|---|---|---|
| Water, $10^6$ gal/yr | 2.3 | 9.03 | 12.2 |
| (8.53/1000 gal) | $ 1,196 | 4,786 | 6,495 |
| Electricity, $10^6$ kwh/hr | 4.72 | 9.64 | 27.9 |
| ($0.05/kwh) | $ 236,000 | 482,000 | 1,395,000 |
| Fuel, gal/hr | 83,856 | 117,360 | 335,520 |
| ($1.20/gal) | 46,628 | 140,832 | 402,624 |
| Spare Parts 6% Capital Equipment (with design) | $ 296,513 | 584,239 | 1,386,658 |
| Materials/Supplies 10% other operating | $ 133,034 | 256,186 | 574,078 |
| Total Direct Costs | $1,463,370 | 2,818,043 | 6,314,855 |

TABLE I-11. COLLOCATED SITE OPERATING COSTS
SHAFT FURNACE

| Agent Rate | 1000 lb/hr (3 units) | 3000 lb/hr (8 units) | 5000 lb/hr (13 units) |
|---|---|---|---|
| Water, $10^6$ gal/yr | 12.2 | 36.8 | 6.13 |
| (0.53/1000 gal) | $ 6,495 | 19,485 | 32,548 |
| Electricity, kwh/yr | 27.9 | 70.7 | 113.6 |
| ($0.05/kwh) | $1,395,000 | 3,535,000 | 5,680,000 |
| Fuel, gal/hr | 335,520 | 921,920 | 1,510,000 |
| ($1.20/gal) | $ 402,624 | 1,106,304 | 1,820,000 |
| Spare Parts 6% Capital Equipment (with design) | $1,386,658 | 4,405,953 | 7,126,920 |
| Materials/Supplies 10% other operating | $ 574,078 | 1,386,674 | 2,150,947 |
| Total Direct Costs | $6,314,855 | 15,253,416 | 23,660,415 |

TABLE I-12. SINGLE SITE TOTAL LIFE OPERATING COST - SHAFT FURNACE

| Period | Labor Cost/Yr | | | Other Direct Costs/Yr | | | Duration | | | Total Cost | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 100 | 400 | 1000 | 100 | 400 | 1000 | 100 | 400 | 1000 | 100 | 400 | 1000 |
| Eq Acceptance | 250,000 | 450,000 | 850,000 | 487,790 | 939,348 | 2,104,952 | 0.5 | 0.5 | 0.5 | 368,895 | 694,674 | 1,477,476 |
| Training and System | 750,000 | 1,350,000 | 2,550,000 | 731,685 | 1,409,022 | 3,157,428 | 0.5 | 0.5 | 0.5 | 740,843 | 1,379,511 | 2,853,714 |
| A, B/C, D (No changeout) | 750,000 | 1,350,000 | 2,550,000 | 1,463,370 | 2,818,043 | 6,314,855 | 7.26 | 1.83 | 0.75 | 16,069,066 | 7,627,519 | 6,648,641 |
| Shutdown | 250,000 | 450,000 | 850,000 | 487,790 | 939,348 | 2,104,952 | 0.5 | 0.5 | 0.5 | 368,895 | 694,674 | 1,477,476 |
| TOTAL | | | | | | | | | | 17,547,699 | 10,396,378 | 12,457,307 |

TABLE I-13. COLLOCATED SITE TOTAL LIFE OPERATING COST - SHAFT FURNACE

| Period | Labor Cost/Yr | | | Other Direct Costs/Yr | | | Duration | | | Total Cost | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1000 | 3000 | 5000 | 1000 | 3000 | 5000 | 1000 | 3000 | 5000 | 1000 | 3000 | 5000 |
| Eq Acceptance | 850,000 | 1,600,000 | 2,283,333 | 2,104,951 | 5,084,472 | 7,886,805 | 0.5 | 0.5 | 0.5 | 1,477,476 | 3,342,236 | 5,085,069 |
| Training and System | 2,550,000 | 4,800,000 | 6,850,000 | 3,157,428 | 7,626,708 | 11,830,206 | 0.5 | 0.5 | 0.5 | 2,853,714 | 6,213,354 | 9,340,104 |
| A, B/C, D (No changeout) | 2,550,000 | 4,800,000 | 6,850,000 | 6,314,855 | 15,253,416 | 23,660,415 | 6.34 | 2.46 | 1.5 | 56,203,61 | 49,331,403 | 45,765,623 |
| Shutdown | 850,000 | 1,600,000 | 2,283,333 | 2,104,951 | 5,084,472 | 7,886,805 | 0.5 | 0.5 | 0.5 | 1,477,476 | 3,342,236 | 5,085,069 |
| TOTAL | | | | | | | | | | 62,011,847 | 62,229,229 | 65,275,865 |

TABLE I-14. DEVELOPMENT COSTS SHAFT FURNACE

| Phase II | Lab Studies |
|---|---|
| Concept Refinement | $ 15,000 |
| Blast Attenuation Studies (includes materials) | 400,000 |
| Detonation Rate Studies (includes materials) | 400,000 |
| Refractory-Materials Compatability Studies | 150,000 |
| Environmental Studies | 100,000 |
| Feasibility Studies | 85,000 |
| Conceptual Design Studies | 60,000 |
| Subcontractors | 200,000 |
| Contingencies | 60,000 |
| TOTAL | $1,470,000 |
| **Phase III** | **Pilot Studies** |
| Conceptual Design | $ 250,000 |
| Test Plant | 40,000 |
| Pilot Plant Construction | 3,793,100 |
| Operation (1 yr) (includes start-up and training) | 1,406,448 |
| Test Reports | 15,000 |
| Process Development | 700,000 |
| 30% Design Package | 400,000 |
| Subcontractors | 500,000 |
| Subtotal | $7,104,548 |
| Contingencies (20%) | $1,420,910 |
| Total Phase III | $8,525,458 |
| TOTAL DEVELOPMENT COSTS | |

TABLE I-15. TOTAL LIFE CYCLE COSTS
SHAFT FURNACE

| Agent Rate | Single Site 100 lb/hr (1 unit) | 400 lb/hr (1 unit) | 1000 lb/hr (3 units) |
|---|---|---|---|
| Capital | $ 6,572,880 | 11,457,774 | 28,013,990 |
| Operating | $ 17,547,699 | 10,396,378 | 12,457,307 |
| Development | $ 10,000,000 | 10,000,000 | 10,000,000 |
| TOTAL LIFE CYCLE | $ 34,120,579 | 31,854,152 | 50,471,297 |
| | **Collocated Site** | | |
| | 1000 lb/hr (3 units) | 3000 lb/hr (8 units) | 5000 lb/hr (13 units) |
| Capital | $ 28,013,990 | 86,371,027 | 139,692,540 |
| Operating | $ 62,011,847 | 62,229,229 | 65,275,865 |
| Development | $ 10,000,000 | 10,000,000 | 10,000,000 |
| TOTAL LIFE CYCLE | $100,025,840 | 158,600,260 | 214,968,410 |

FIGURE I-2

# SHAFT FURNACE CONCEPT

## LIFE CYCLE COST CURVES
## SINGLE SITE
## FEEDSTOCK B

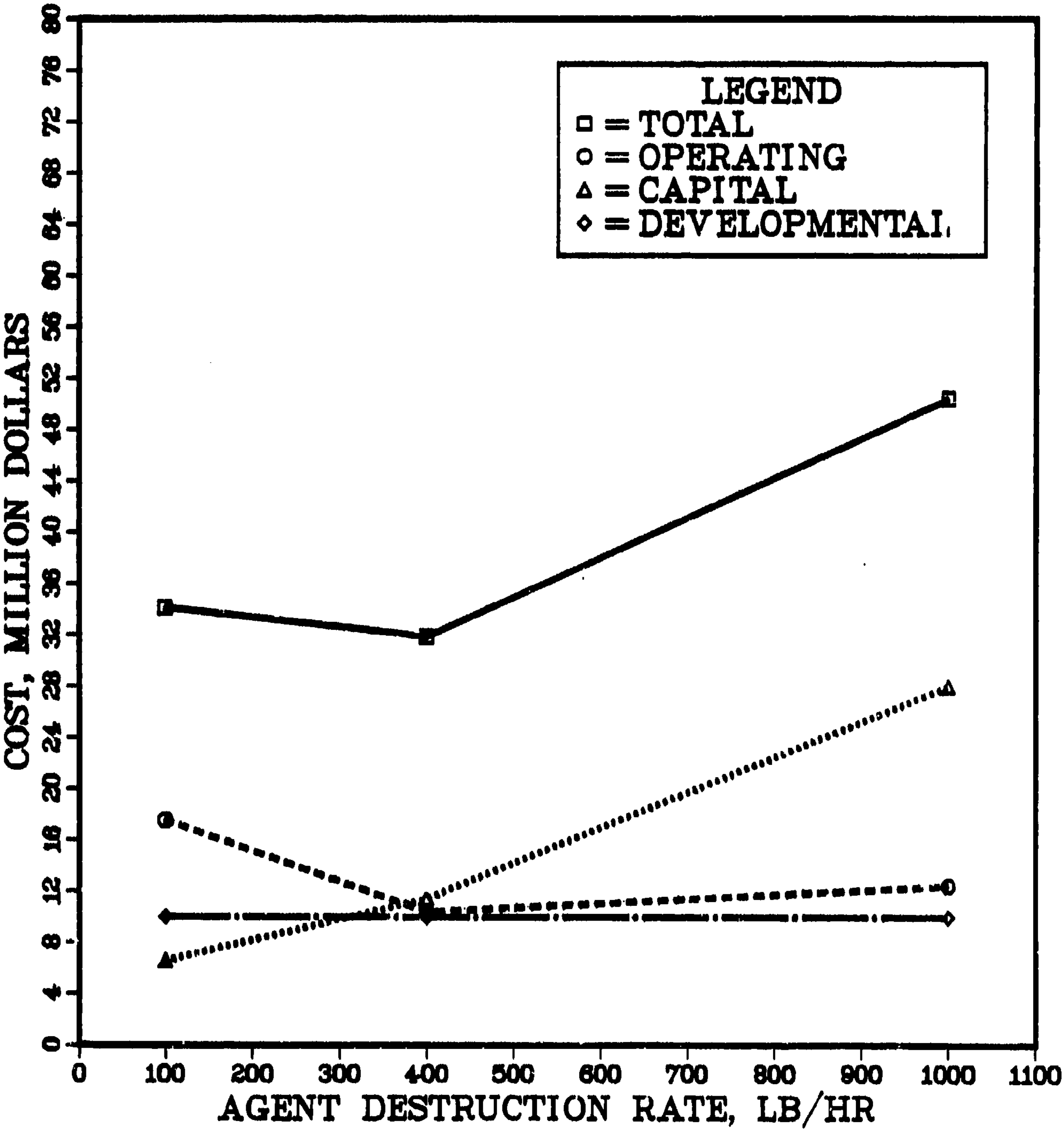
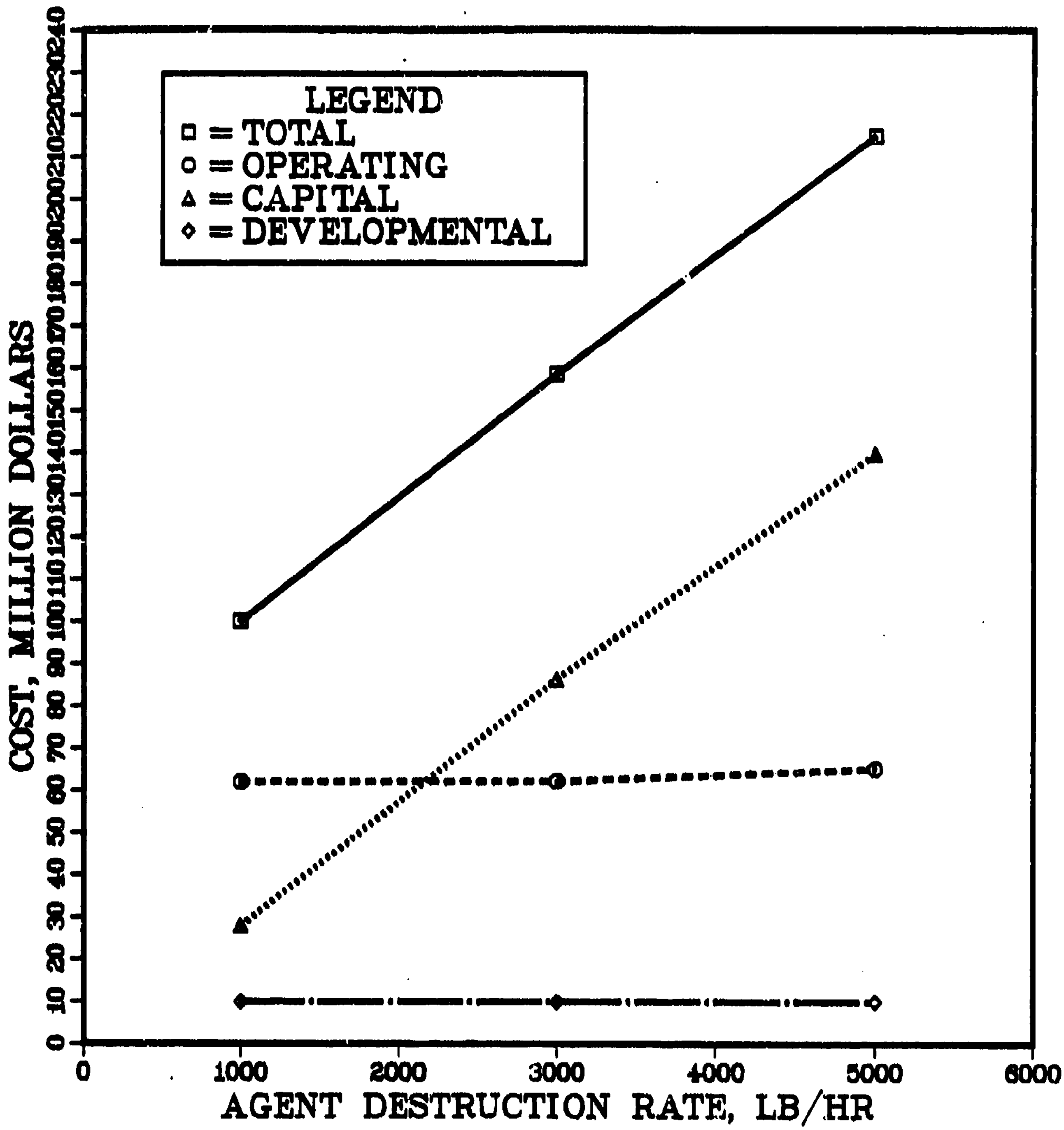


FIGURE I-3

# SHAFT FURNACE CONCEPT

## LIFE CYCLE COST CURVES
## COLLOCATED SITE
## FEEDSTOCK B



F. Optimum Process Flow Rate

The life cycle cost curves indicate that a minimum total cost is achieved at a 400 lb/hr agent destruction rate.

G. Operating Time

The single and collocated operating times are listed in Tables I-16 and I-17. The operating time corresponding to the minimum total cost destruction rate (400 lb/hr) is 1.83 years.

TABLE I-16. SINGLE SITE OPERATING TIME - SHAFT FURNACE

| Munition Category | Munition Type | Inventory | Through-put Per Hour 100 lb/hr | 400 lb/hr | 1000 lb/hr | System* Availability | Production Years 100 lb/hr | 400 lb/hr | 1000 lb/hr |
|---|---|---|---|---|---|---|---|---|---|
| A | M55 Rockets | 80,000 | 9.3 | 37.4 | 93.5 | 0.8 | 2.15 | 0.54 | 0.21 |
| | M23 Mines | 20,000 | 9.5 | 38.1 | 95.2 | 0.8 | 0.53 | 0.13 | 0.05 |
| B/C | Mortars | 50,000 | 16.7 | 66.7 | 166.7 | 0.8 | 0.75 | 0.18 | 0.08 |
| | 105 mm Projectiles | 50,000 | 62.5 | 250.0 | 625.0 | 0.8 | 0.20 | 0.05 | 0.02 |
| | 155 mm Projectiles | 50,000 | 15.4 | 61.5 | 153.8 | 0.8 | 0.82 | 0.20 | 0.09 |
| | 8" Projectiles | 50,000 | 6.9 | 27.6 | 69.0 | 0.8 | 1.81 | 0.45 | 0.18 |
| D | Bombs | 800 | 0.4 | 1.8 | 4.6 | 0.8 | 0.50 | 0.11 | 0.04 |
| | Ton Containers/ Spray Tanks | 200 | 0.1 | 0.3 | 0.7 | 0.8 | 0.50 | 0.17 | 0.08 |
| | TOTAL | | | | | | 7.26 | 1.83 | 0.75 |

* Based on Thermal System only.

TABLE I-17. COLLOCATED SITE OPERATING TIME - SHAFT FURNACE

| Munition Category | Munition Type | Inventory | Through-put Per Hour | | | System* | Production Years | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | 1000 lb/hr | 3000 lb/hr | 5000 lb/hr | Availability | 1000 lb/hr | 3000 lb/hr | 5000 lb/hr |
| A | M55 Rockets | 800,000 | 93.5 | 280.4 | 467.3 | 0.8 | 2.14 | 0.71 | 0.43 |
| | M23 Mines | 200,000 | 95.2 | 285.7 | 476.2 | 0.8 | 0.53 | 0.17 | 0.11 |
| B/C | Mortars | 500,000 | 166.7 | 500.0 | 833.3 | 0.8 | 0.75 | 0.25 | 0.15 |
| | 105 mm Projectiles | 500,000 | 625.0 | 1875.0 | 3125.0 | 0.8 | 0.20 | 0.06 | 0.04 |
| | 155 mm Projectiles | 500,000 | 153.8 | 465.5 | 769.2 | 0.8 | 0.82 | 0.27 | 0.16 |
| | 8" Projectiles | 500,000 | 59.0 | 206.9 | 344.8 | 0.8 | 0.74 | 0.60 | 0.37 |
| D | Bombs | 8,000 | 4.5 | 13.6 | 22.7 | 0.8 | 0.44 | 0.15 | 0.09 |
| | Ton Containers/ Spray Tanks | 2,000 | 0.7 | 2.0 | 3.3 | 0.8 | 0.72 | 0.25 | 0.15 |
| | TOTAL | | | | | | 6.34 | 2.46 | 1.5 |

* Based on Thermal System only.

APPENDIX J

ENGINEERING AND ECONOMIC ANALYSIS - MOLTEN SALT

# APPENDIX J

## ENGINEERING AND ECONOMIC ANALYSIS - MOLTEN SALT

### Engineering Analysis

#### A. System Concept Description

The molten salt concept is shown in Figure J-1. A mash (chunk size 6 in. or less) including agent, explosives, metal and dunnage (feed configuration h) is fed to the molten salt combustors along with oxygen enriched air and make-up soda ash. The molten salt combustor contains a bed of molten salt at a nominal 1800 F and a pool of molten metal at 2600 F. The metal is melted and maintained in a molten state by an electrical induction furnace. Excess heat from the combustion of the agent, explosives and dunnage is removed by cooling air. The resultant combustion gases require cooling and collection of particulates in a bag-house before release to the atmosphere. Decontaminated molten salt and molten metal are drawn off at separate taps.

A detailed flow sheet of a bank of molten salt combustors operating in parallel is shown in Figure J-2. The maximum through-put for one unit is estimated at 500 pounds per hours of agent and related materials. Multiple units are required at higher agent feed rates. The overall system mass balance is shown in Table J-1 and the overall system heat balance is shown in Table J-2.

#### B. System Feed Requirements

The feed system required for this system is feedstock h, mashed munitions of 6 in. or less. The system could also accept feedstock g, cut, sawed or sheared munitions if they are 6 in. or less in size. The feedstock must be fed below the surface of the molten

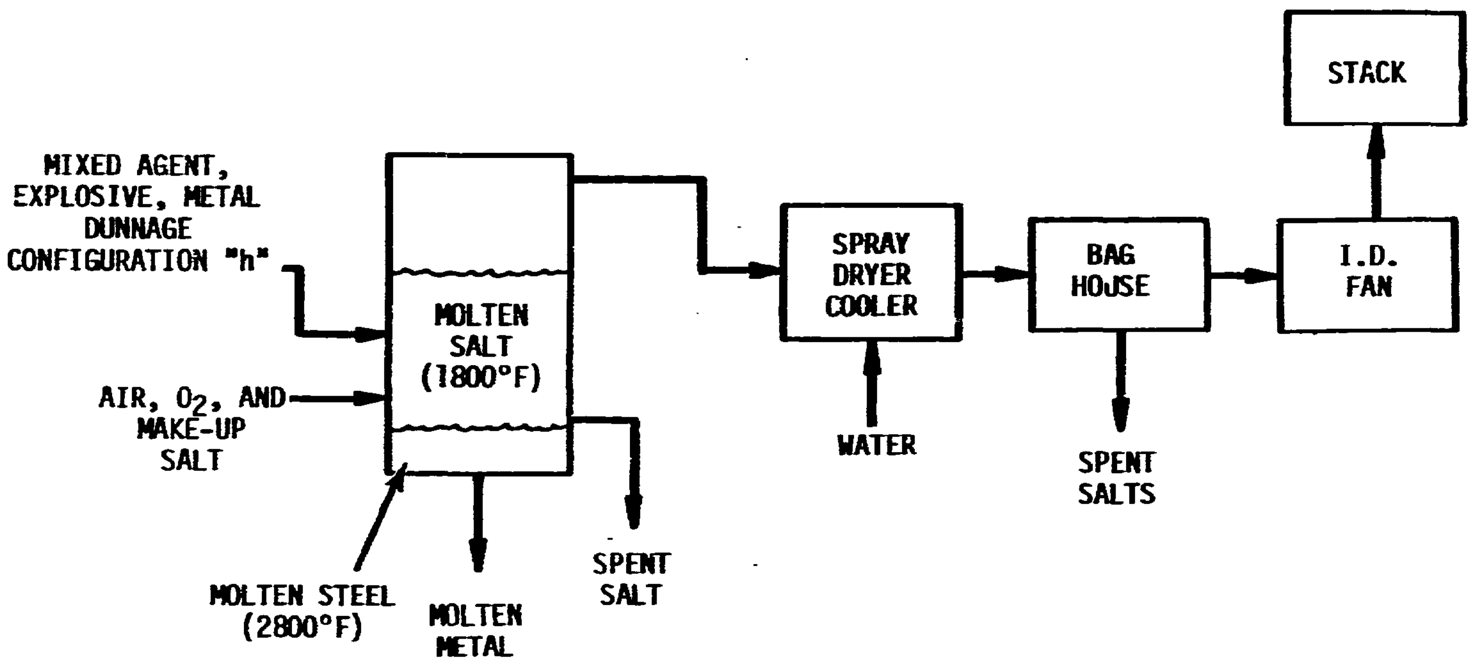



FIGURE J-1. MOLTEN SALT SYSTEM CONCEPT

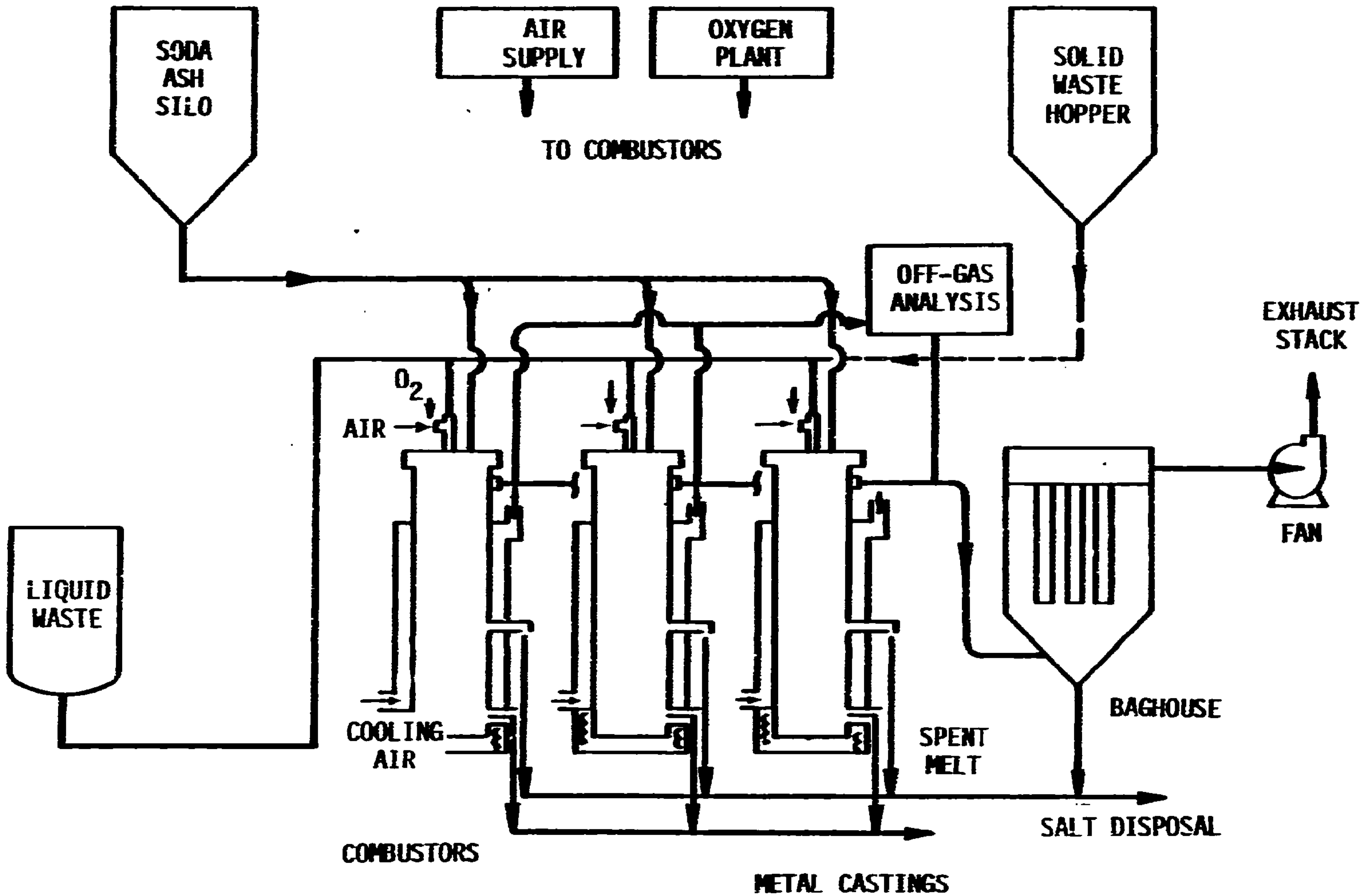



FIGURE J-2. MOLTEN SALT SYSTEM CONCEPT
USING A BANK OF MOLTEN SALT UNITS

TABLE J-1. MOLTEN SALT MASS BALANCE
400 LB/HR AGENT FEED RATE

| Material | lb/hr |
|---|---|
| **IN** | |
| Wood | 650 |
| GB | 400 |
| Explosive | 250 |
| Air | 4,660 |
| Water | 2,400 |
| Soda Ash | 600 |
| $O_2$ 90% | 1,760 |
| Metal | 2,050 |
| TOTAL | 12,770 |
| **OUT** | |
| Flue gas w/water | 9,938 |
| Metal | 2,050 |
| Particulate | 206 |
| Spent Salt | 576 |
| TOTAL | 12,770 |

TABLE J-2. MOLTEN SALT HEAT BALANCE
400 LB/HR AGENT FEED RATE

IN

| Material In | HHV | Btu/hr |
|---|---|---|
| Wood | 8,500 | 5,525,000 |
| GB | 10,073 | 4,029,200 |
| Explosive | 5,400 | 1,350,000 |
| Electrical | -- | 851,400 |
| TOTAL | | 11,755,600 |

OUT

| Material Out | Cp | T | Btu/hr |
|---|---|---|---|
| Water in flue gas* | 0.50 | 1,730 | 2,743,830 |
| Flue gas | 0.25 | 330 | 819,885 |
| Metal* | 0.11 | 2,730 | 851,400 |
| Particulate | 0.25 | 330 | 16,995 |
| Spent Salt* | 0.25 | 1,730 | 370,080 |
| Heat Losses | by difference | | 6,953,410 |
| TOTAL | | | 11,755,600 |

* Includes heat of vaporization or heat of fusion.

salt to insure capture of the gaseous pollutants in the molten salt bath. This requires the feed to be such that the liquids in the feed material can be readily released and not result in pockets of high pressure that would result in unstable operation of the unit.

C. Pollution Abatement System

The molten salt bath is an insitu pollution control. The sodium carbonate in the melt reacts with the resultant off gases from the combustion of the agent, explosives and dunnage as they pass through the froth of molten salt. The $SO_2$, HCl, $P_2O_5$ and HF react with the sodium carbonate to form the sodium salts. The remaining off-gas requires only cooling and collection of particulates in a baghouse before being released to the atmosphere.

D. Ultimate Disposal

The residues generated from the incineration of the agent and related materials are molten metal, molten salt and collected particulate. The molten metal and molten salt are drawn off at seperate taps. The molten metal can be cast or quenched in a water tank. The casting would form large blocks of metal that would require hours of cooling time. The quenching would form small balls of metal that could be handled easily. The quenching was the method assumed in this evaluation. The molten salt is cast into 55 gallon drums for cooling and storage in this evaluation. The collected particulates in the baghouse are the salts that have been carried off of the molten salt bath. The salt particulate is drummed and stored in this evaluation. The total volume of salt for this process is less than in some other processes because the casting of the molten salt achieves a greater density in the drums.

## E. System Concept Advantages

The advantages to the molten salt process is that the gaseous emissions are cleaned of noxious gases in the molten salt bath as they pass through it. This eliminates the need for spraying a salt solution in the flue gas to scrub out noxious gases.

The casting of the molten salt from the process greatly reduces the volume of the salts generated. This reduces storage costs or landfill costs (if the salts can be landfilled).

The quenching of the molten metal generates a metal scrap that is easy to handle and has a higher bulk density than jagged, irregular-shaped metal scrap. This reduces handling costs of the decontaminated metal scrap.

## F. System Concept Disadvantages

The system disadvantages include the fact that a water quench or spray dryer and baghouse are still required in the pollution control system so there is little savings of cost of the pollution control system. There is a slight reduction in the amount of flue gas from the use of oxygen in the molten salt unit, however, there is the additional oxygen handling equipment that is required. Most importantly there is the question of materials compatability because of the action of the salt on the refractory.

## G. System Concept Knowledge Gaps

Knowledge gaps exist in several areas. The distribution of phosphorus between the molten salt and off-gas is unknown and may depend on bed geometry. Excess $P_2O_5$ in the baghouse could result in caking. The compatibility of aluminum with the salt bath must be investigated. A thermite type reaction might occur.

Uncertainties include the effect of vaporization of salt at the metal-salt interface. There is also the uncertainty with materials compatibility at this interface.

## H. Safety

The molten salt system is safe. The system operates at negative pressure to eliminate leaks. The feed is kept cool until it is fed below the surface of the molten salt bed. The combustion product must pass through a froth of molten salt that provides high heat transfer to the gases insuring rapid and complete destruction of the chemical agent before leaving the combustor.

## I. Likelihood of Developments Within 5 Years

Molten salt systems without the molten metal part of the system have been used for pesticide destruction and coal gasification. The addition of the molten metal induction furnace to the molten salt system will result in increased development time but should not exceed 5 years. The likelihood of development of the molten salt concept system within 5 years is good.

## J. Scalability

Capacity of the molten salt combustion is limited by superficial velocity of gas in the bath. Rockwell will not project beyond a 6 foot diameter beds with assurance of sufficient bed turbulence for complete agent destruction. Scaling is thus done by adding or removing units for various agent feed rates.

## K. Degree of Technical Risk

The molten salt system has a moderate degree of technical risk. The major risk is the molten salt/molten metal interface. If

the interface cannot be achieved due to the temperature difference and/or reactions that may occur, the process will have to be modified to remove metal scrape from the molten salt bath by mechanical means. This would make the system more complex, involve high maintainence and require a seal system where the metal is removed.

## L. RAM Factors

The overall thermal system availability factor used for the economic evaluation was 0.928. The factor was calculated similar to those in Appendix L.

## M. Materials Compatibility

The major area of materials compatibility problems is the molten salt combustor. The molten metal portion operating at 2800 F itself is not a problem. There is much experience from the steel industry. The problem arises at the interface due to potential salt vapors and the 1000 F temperature difference. Furthermore, the slag chemistry at the salt/metal interface is unknown.

The rest of the materials compatibility problems are of less concern than in baseline due to the majority of the corrosive gases being captured in the molten salt combustor.

## N. Energy Requirements and Source

The molten salt concept requires fuel oil and electricity. The fuel oil is needed during idle periods to maintain temperature in the molten salt bath. The fuel oil usage is estimated by Rockwell at 45 gallons per hour for a 500 pound per hour molten salt unit. This calculates to 6.4 MMBtu per hour which indicates to a high heat loss from the system. The system also requires electric power for the pollution control system, mainly the induced draft fan, and the metal

induction furnace. The metal induction furnace uses most of its power during operation when metal is being melted.

O. Ease of Operation

The complexity of the thermal system is minimized since the system consists of only one system. The furnace itself has no moving parts also reducing its complexity.

The flexibility of the system is limited. The feedstock size is restricted and detonable items such as fuzes may cause problems. After demilitarization operation the molten salt system would be limited in use or complicated because of the molten metal bath at the bottom of the molten salt bath.

The operability is good because of its simplicity. Start-up and shutdown for extended periods may be a problem. The salts and metal must be melted during startup and drained before shutdown.

# Economic Analysis - Molten Salt

## A. Facility Costs

Some equipment sizing and costing is included in this section because it is closely related to, and necessary for the determination of facility cost.

Molten Salt Furnace. The furnace design is based upon modular combustion vessels and auxiliary assemblies. A single combustion module is rated at 500 lb/hr agent and related material. This translates to 13.5 MMBtu/hr heat release. Each module and related hardware costs are $2,700,000, based on a phone call to Rockwell December 22, 1982.

| Agent Feed Rate | # of Units | Cost, $10^6$ |
|---|---|---|
| 100 | 1 | 1.03 |
| 400 | 1 | 2.7 |
| 1000 | 2 | 5.4 |
| 3000 | 6 | 16.2 |
| 5000 | 10 | 27.0 |

Each module (full size) is 8 feet OD. An estimate of 8 feet clearance is used in determining the size of the room.

| Agent Feed Rate | Room Dimensions | $400/ft$^2$ Sq. Ft | $ |
|---|---|---|---|
| 100 | 20 x 20 | 400 | 160,000 |
| 400 | 25 x 25 | 625 | 250,000 |
| 1000 | 50 x 25 | 1250 | 500,000 |
| 3000 | 75 x 50 | 3750 | 1,500,000 |
| 5000 | 125 x 50 | 6250 | 2,500,000 |

Molten Metal Handling Area.

| Agent Rate | Metal Rate |
|---|---|
| 100 | 510 |
| 400 | 2,050 |
| 1000 | 5,130 |
| 3000 | 15,400 |
| 5000 | 25,650 |

There are two approaches to handling the molten metal. The first is to cast the molten iron into pigs and the second is to pour the molten iron into a water vat to quench the steel. It is envisioned that the iron will form spheres of iron that can be removed from the bottom of the vat by a drag conveyor.

For the purposes of the economic analysis, the quench tank was assumed for all operations.

The vat would be a tank of water 8 feet deep and 5 feet square. The water temperature could be at 212 and not cause any problems. The amount of water used at steady-state conditions is estimated at

| Agent Rate lb/hr | Metal Rate lb/hr | Water Rate gal/hr |
|---|---|---|
| 100 | 510 | 25 |
| 400 | 2,050 | 100 |
| 1000 | 5,130 | 250 |
| 3000 | 15,400 | 740 |
| 5000 | 25,650 | 1,230 |

Heat Capacity of steel - 0.11 Btu/lb

Heat of Fusion - 115 Btu/lb

Melting Point - 2785°F (use 3000°F)

$$Q = (1)(.11)(3000-212)+115 = 422 \text{ Btu/lb of steel}$$

8780 Btu/gal water = 0.048 gal water/lb steel

The vat should be able to handle up to 1000 lb/hr agent feed metal content of 5,130 lb/hr of steel. For higher feed rates will use two molten salt units feeding 1 water quench vat.

Area required for each vat is 10 ft x 20 ft. The metal is 5 x deconned and is piped into an adjoining room where it is quenched. The room cost is $90/ft^2$.

| Agent Rate | $ |
|---|---|
| 100 | 18,000 |
| 400 | 18,000 |
| 1000 | 18,000 |
| 3000 | 54,000 |
| 5000 | 90,000 |

Molten Salt Handling Area. The molten salt will be piped to an adjoining room and cast into drums. Each module at full capacity will generate 750 lb/hr of salts.

sp.gr of $Na_2CO_3$ is 2.532.

(2.532)(8.33)(55) = 1160 lb/55 gallons if in solid crystalline form. This would require 1 drum per hour per module at full capacity based on 1.5 pound of salt produced per pound of agent destroyed. Assume one salt drumming station per module. Each salt drumming station will use an estimated 10 ft x 10 ft. Used $90/ft^2$.

| Agent Rate | $ft^2$ | $ |
|---|---|---|
| 100 | 100 | 9,000 |
| 400 | 100 | 9.000 |
| 1000 | 200 | 18,000 |
| 3000 | 600 | 54,000 |
| 5000 | 1000 | 90,000 |

APC Pad. The APC consists of a water quench unit followed by a baghouse. The use of oxygen will reduce the flue gas flowrate by about 70 percent. The equipment will be very similar to baseline so baseline areas will be scaled from

Baseline 400 lb/hr - 2500 $ft^2$ at $2.5/$ft^2$ - $6,260

Baseline 3000 lb/hr - 6570 $ft^2$ at $2.5/$ft^2$ - $16,425

| | | |
|---|---|---|
| 100 | $(6250)\left(\frac{100}{400}\right)(.3)^{.6}$ = $1320 | (528 $ft^2$) |
| 400 | $(6250)(.3)^{.6}$ = $3030 | (1214 $ft^2$) |
| 1000 | $(16425)\left(\frac{1000}{3000}\right)(.3)^{.6}$ = $4125 | (1650 $ft^2$) |
| 3000 | $(16425)(.3)^{.6}$ = $7980 | (3190 $ft^2$) |
| 5000 | $(16425)\left(\frac{5}{3}\right)(.3)^{.6}$ = $10840 | (4335 $ft^2$) |

Fuel and $O_2$ Tank Pad. Fuel usage occurs during weekends and 4 hours a day at a rate of 45 gallons per hour. During this time $O_2$ will not be used, air will be used.

Fuel usage will be:

$$(45)(4)(250) + (365-250)(24)(45) = 169{,}200 \text{ gal/yr}$$

One baseline tank (14,700 gal) filled once a month will handle each module unit.

100 lb/hr. Smaller than one unit will use half a 14,700 gal tank.

$\left(\frac{.5}{2}\right)1320$ = 330 $ft^2$ at $2.5/$ft^2$ $900

400 lb/hr. One tank.

$(\frac{1}{2})(1320)$ = 660 $ft^2$ $1650

1000 lb/hr. Two tanks.

1320 $ft^2$ $3300

3000 lb/hr. Six tanks.

(3)(1320) = 3960 $ft^2$ $9900

<u>5000 lb/hr</u>. Ten tanks.

$$(5)(1320) = 6600 \text{ ft}^2 \quad \$16,500$$

Oxygen usage is 1.5 lb/lb agent feed.

$$\left(\frac{1.5}{32}\right)(379) = 17.77 \text{ scf/lb agent}$$

| Agent Rate | $O_2$ | $O_2$ |
|---|---|---|
| 100 | 1777 $ft^3$/hr | 30 scfm |
| 400 | 7106 $ft^3$/hr | 118 scfm |
| 1000 | 17,766 $ft^3$/hr | 296 scfm |
| 3000 | 53,297 $ft^3$/hr | 888 scfm |
| 5000 | 88,828 $ft^3$/hr | 1480 scfm |

A 13,000 gal liquid gas tank with vaporizor rental cost in 1981 was $1075/month.

$$1075\left(\frac{746}{721.3}\right) = \$1200\text{/month (rounded up)}$$

$$(13{,}000 \text{ gal})(7.13 \text{ lb/ft}^3)(0.13368055 \text{ ft}^3\text{/gal}) = 123{,}908 \text{ lbs}$$
$$= 7{,}146{,}540 \text{ scf}$$

Tank will occupy a 15' x 15' pad - $560. This tank will provide 3335 scfh for one month. Will scale from this number.

<u>100 lb/hr</u>.

$$\left(\frac{1777}{3335}\right)^{.6} 560 = \$380$$

<u>400 lb/hr</u>.

$$\left(\frac{7106}{3335}\right)^{.6} 560 = \$880$$

<u>1000 lb/hr.</u>

$$\left(\frac{17,766}{3335}\right)^{.6} 560 = \$1530$$

<u>3000 lb/hr.</u>

$$\left(\frac{53,297}{3335}\right)^{.6} 560 = \$2950$$

<u>5000 lb/hr.</u>

$$\left(\frac{88,828}{3335}\right)^{.6} 560 = \$4010$$

Total Pad (Fuel and $O_2$):

| | |
|---|---|
| 100 | \$ 1,700 |
| 400 | 3,910 |
| 1000 | 5,660 |
| 3000 | 10,930 |
| 5000 | 14,850 |

<u>Salt and Drum Storage</u>. Baseline data is based on using NaOH and the amount of salts generated at CAMDS. The drums are 55 gallon drums and are loaded with the dry salts without packing or shaking. A bulk density of 40 lb/ft$^3$ is assumed. (This value is for flyash, untapped). From calculations the amount of salt generated per pound of GB incinerated using a stoichiometric ratio of 2 amounts to 371 lb/lb GB agent incinerated. Molten salt has a salt makeup of 1.5 lb/lb GB and this is also assumed to be the amount of salts generated. Another difference that arises is that the salts generated from the molten salt process is cast/poured into the 55-gallon drums resulting in a reduction in barrel usage. The density of the molten salt is estimated at 1/2 of the crystalline density of the sodium salts that range from 2.0 to 2.5 $(2.25)(.5) = 1.13$

$$(1.13)(62.4) = 70 \text{ lb/ft}^3$$

The difference in salt generation amounts to

$$\left(\frac{3.71}{1.5}\right)\left(\frac{70}{40}\right) = 4.33.$$

Will use a difference of 4 times the volume of salt generation.

Baseline at 400 lb/hr agent has a cost of \$150,800.

<u>100 lb/hr</u>.

$$\left(\frac{100}{400}\right)\left(\frac{1}{4}\right)^{.6} 150{,}800 = \$28{,}580$$

<u>400 lb/hr</u>.

$$\left(\frac{1}{4}\right)^{.6} 150{,}800 = \$65{,}640$$

<u>1000 lb/hr</u>.

$$\left(\frac{1000}{3000}\right)\left(\frac{1}{4}\right)^{.6} 397{,}290 = \$89{,}450$$

<u>3000 lb/hr</u>.

$$\left(\frac{1}{4}\right)^{.6} 397{,}290 = \$172{,}930$$

<u>5000 lb/hr</u>.

$$\left(\frac{5000}{3000}\right)\left(\frac{1}{4}\right)^{.6} 397{,}290 = \$234{,}950$$

The above calculations are compiled in Tables J-3 and J-4.

<u>Capital Equipment</u>

Some equipment costs are presented in the above sections.

<u>Molten Salt Furnace</u>. See facility costs.

TABLE J-3. SINGLE SITE FACILITY COSTS - MOLTEN SALT

| Facility | 100 lb/hr | 400 lb/hr | 1000 lb/hr |
|---|---|---|---|
| Molten Salt Furnace | $160,000 | $250,000 | $500,000 |
| Molten Metal Handling | 18,000 | 18,000 | 18,000 |
| Molten Salt Handling | 9,000 | 9,000 | 18,000 |
| APC Pad | 1,320 | 3,030 | 4,130 |
| Fuel and Oxygen Tank Pad | 1,700 | 3,910 | 5,660 |
| Salt and Drum Storage | 28,580 | 65,640 | 89,450 |
| TOTAL | $218,600 | $349,580 | $635,240 |
| Baseline: $1,058,330 | | | |

TABLE J-4. COLLOCATED SITE FACILITY COSTS - MOLTEN SALT

| Facility | 1000 lb/hr | 3000 lb/hr | 5000 lb/hr |
|---|---|---|---|
| Molten Salt Furnace | $500,000 | $1,500,000 | $2,500,000 |
| Molten Metal Handling | 18,000 | 54,000 | 90,000 |
| Molten Salt Handling | 18,000 | 54,000 | 90,000 |
| APC Pad | 4,130 | 7,980 | 10,840 |
| Fuel Tank Pad | 5,660 | 10,930 | 14,850 |
| Salt and Drum Storage | 89,450 | 172,930 | 234,950 |
| TOTAL | $635,240 | $1,799,840 | $2,940,640 |
| Baseline: $2,779,265 | | | |

| Agent Rate | Units | $ x 10^6 |
|---|---|---|
| 100 | 1 | 1.03 |
| 400 | 1 | 2.7 |
| 1000 | 2 | 5.4 |
| 3000 | 6 | 16.2 |
| 5000 | 10 | 27.0 |

Molten Metal Handling Eq. For the cost of the vat will be based on a 1500 gallon tank and a 48-inch wide belt conveyor. The belt will be perforated and have peddles to remove water and carry the steel up the incline. Each tank will cost

$$(3{,}000 \times 1.96)\ \frac{746}{273.1} = \$16{,}100$$

(Guthrie, March 24, 1969, Chem. Eng., Figure 14)

The conveyor length will be 5 ft. plus 12 ft plus 8 ft. The runs correspond to the bottom of the tank, the rise, and an 8-foot horizontal run. The cost is

$$(\$750/\text{ft})(25\ \text{ft})(1.64)\left(\frac{746}{273.1}\right) = \$84{,}000.$$

Each unit will cost $100,100.

| | # Units | Cost | | Adjustment |
|---|---|---|---|---|
| 100 | 1 | 100,100 | $(.1)^{.6}$ | 25,200 |
| 400 | 1 | 100,100 | $(.4)^{.6}$ | 57,800 |
| 1000 | 1 | 100,100 | 1 | 100,000 |
| 3000 | 3 | 300,000 | 1 | 300,300 |
| 5000 | 5 | 500,500 | 1 | 500,000 |

Molten Salt Drumming and Handling Eq. Each molten salt module is estimated to produce 1 55-gallon drum per hour of salts. This is a rate that will be done manually. The equipment will consist of a stainless steel line electrically heated to keep the salts molten. The line will provide two discharge points. There will be a

vent hood over the discharge points to remove heat and noxious fumes. The drums will be fill on carts that can be moved to the loading area for further cooling. Costs are estimated as follows:

| | |
|---|---|
| Carts at $500 each | $ 500 |
| Ver. hood with blower | 2,000 |
| Header System | 5,000 |
| Total for each molten salt module | $7,500 |

| | # Units | Cost |
|---|---|---|
| 100 | 1 | $7,500 |
| 400 | 1 | 7,500 |
| 1000 | 2 | 15,000 |
| 3000 | 6 | 45,000 |
| 5000 | 10 | 75,000 |

Water Quench. With each lb of GB agents, 0.63 lb of explosive and 1.63 pound of dunnage will be included. Each lb of GB produces roughly 30 $ft^3$ of flue gas when burned in $O_2$. Each pound of wood will produce roughly 30 $ft^3$ of flue gas when burned in $O_2$. Explosives are self-sufficient for combustion. Each lb of explosive is assumed to release 100 cu ft of gas. The total flue gas release per pound of agent and related material is

$$30 + 48.9 + 63 = 142 \ ft^3/lb$$

at

| lb/hr | scfm | acfm at 1800° F |
|---|---|---|
| 100 | 600 | 2,600 |
| 400 | 2,300 | 10,000 |
| 1000 | 5,700 | 24,800 |
| 3000 | 17,100 | 74,400 |
| 5000 | 28,500 | 123,900 |

These flow rates will be used to cost the quench and baghouse. The cost equation is from Chem. Eng. Jan. 26, 1981 "Cost File"

$$\$(1977) = (0.22 \times ft^3/min) + 2,000.$$

This does not include refractory and pump. 20 percent will be added to cover these costs.

| | |
|---|---|
| 100 | $15,200 |
| 400 | 18,100 |
| 1000 | 23,900 |
| 3000 | 43,200 |
| 5000 | 62,500 |

<u>Baghouse</u>. Baghouse costs will be scaled from baseline.

Baseline: (.6 factor)

2200 scfm - $13,000
11,000 - $400,000

| | | |
|---|---|---|
| 100 | $\left(\frac{600}{2200}\right)^{.6}$ 130,000 | $59,700 |
| 400 | $\left(\frac{2300}{2200}\right)^{.6}$ 130,000 | $133,600 |
| 1000 | $\left(\frac{5700}{2200}\right)^{.6}$ 130,000 | $230,200 |
| 3000 | $\left(\frac{17,000}{11,000}\right)^{.6}$ 400,000 | $521,600 |
| 5000 | $\left(\frac{28,500}{11,000}\right)^{.6}$ 400,000 | $708,200 |

<u>Fuel Tank</u>. See facility calculations for number of tanks at $18,000 each.

| | # | $ |
|---|---|---|
| 100 | .5 | 9,000 |
| 400 | 1 | 18,000 |
| 1000 | 2 | 36,000 |
| 3000 | 6 | 108,000 |
| 5000 | 10 | 180,000 |

Oxygen Tank. Rental cost for 3 years is approximately the installation cost of the tank (36)(1200) = 43,200 assuming an installation cost of 40 percent gives at total cost of \$108,000 for a 3335 scfh tank.

| | | |
|---|---|---|
| 100 | $(\frac{1777}{3335})^{.6}$ 108,000 | \$ 74,100 |
| 400 | $(\frac{7106}{3335})^{.6}$ 108,000 | \$170,100 |
| 1000 | $(\frac{17,766}{3335})^{.6}$ 108,000 | \$294,700 |
| 3000 | $(\frac{53,297}{3335})^{.6}$ 108,000 | \$569,700 |
| 5000 | $(\frac{88,828}{3335})^{.6}$ 108,000 | \$774,000 |

Fork Lift and Residue Handling. See Rotary Kiln costs, Appendix E.

The above calculations are summarized in Tables J-5 and J-6.

C. Operating Costs

| | | |
|---|---|---|
| Electric | 1.0 kwh/lb | 5¢/kwh |
| Salts | 1.5 lb/lb GB | \$120/ton |
| $O_2$ | 1.5 lb/lb | 5¢/lb |

Feedstock h (assume dunnage included).

100 lb/hr Feed.

Electric - (100)(1.0)(24)(250) = 600,000 kWh/yr = \$30,000

Salts - (100(1.5)(20)(250)(120)/(2000) = \$45,000/yr

$O_2$ - (100)(1.5)(20)(250)(0.05) = \$37,500/yr.

400 lb/hr.

Electric - \$120,000

TABLE J-5. SINGLE SITE EQUIPMENT COSTS
MOLTEN SALT

| Equipment | 100 lb/hr | 400 lb/hr | 1000 lb/hr |
|---|---|---|---|
| Molten Salt Furnace | $1,030,000 | $2,700,000 | $5,400,000 |
| Molten Metal Handling Eq | 25,200 | 57,800 | 100,100 |
| Molten Salt Drumming & Handling | 7,500 | 7,500 | 15,000 |
| Water Quench | 15,200 | 18,100 | 23,900 |
| Baghouse | 59,700 | 133,600 | 230,200 |
| Fuel Tanks | 9,000 | 18,000 | 36,000 |
| Oxygen Tank | 71,100 | 170,100 | 294,700 |
| Storage Fork Lift | 22,000 | 22,000 | 44,000 |
| Residue Handling Truck | 65,790 | 65,790 | 131,580 |
| Subtotal | 1,308,490 | 3,192,890 | 6,275,480 |
| Design | 25% | 25% | 25% |
| Total Equipment | 1,635,610 | 3,991,110 | 7,844,350 |
| Total Capital | $1,854,210 | $4,340,690 | $8,479,590 |

TABLE J-6. COLLOCATED SITE EQUIPMENT COSTS - MOLTEN SALT

| Equipment | 1000 lb/hr | 3000 lb/hr | 5000 lb/hr |
|---|---|---|---|
| Molten Salt Furnace | $5,400,000 | $16,200,000 | $27,000,000 |
| Molten Metal Handling Eq | 100,100 | 300,300 | 500,000 |
| Molten Salt Drumming & Handling | 15,000 | 45,000 | 75,000 |
| Water Quench | 23,900 | 43,200 | 62,500 |
| Baghouse | 230,200 | 521,300 | 708,200 |
| Fuel Tanks | 36,000 | 108,000 | 180,000 |
| Oxygen Tank | 294,700 | 569,700 | 774,000 |
| Storage Fork Lift | 44,000 | 44,000 | 66,000 |
| Residue Handling Truck | 131,580 | 173,000 | 288,300 |
| Subtotal | 6,275,480 | 18,004,500 | 29,654,500 |
| Design | 25% | 25% | 25% |
| Total Equipment | 7,844,350 | 22,505,620 | 37,068,120 |
| Total Capital | $8,479,590 | $24,305,460 | $40,008,760 |

Salts - \$180,000

$O_2$ - \$150,000.

1000 lb/hr.

Electric - \$300,000

Salts - \$450,000

$O_2$ - \$375,000.

3000 lb/hr.

Electric - \$900,000

Salts - \$1,350,000

$O_2$ - \$1,125,000.

5000 lb/hr.

Electric - \$1,500,000

Salts - \$2,250,000

$O_2$ - \$1,875,000.

Fuel Oil.

| | |
|---|---|
| 100 | $45(\frac{100}{500})^{.6}$ (4)(250) + (24)(115) = 64,420 gal/hr. |
| 400 | (45)(3760) = 160,200 gal/yr. |
| 1000 | (2)(45)(3760) = 338,400 gal/yr - \$406,080. |
| 3000 | (6)(45)(3760) = 1,014,200 gal/yr - \$1,218,240. |
| 5000 | (10)(45)(3760) = 1,692,000 gal/yr - \$2,030,400. |

Water. Water use will be based on metal and gas quenching rates for metal quenching. Was calculated under facility.

| | | | |
|---|---|---|---|
| 100 | metal - (25 gal/hr)(20)(250) = 125,000/yr | | |
| | gas - $\frac{(600)/(379)(29)(.26)(1800-400)}{8780\ \text{Btu/gal}}$ (20)(250)(60) = 489,430 gal/yr. | | |
| 400 | metal - 500,000 | 2,376,460 gal/yr | $1,300 |
| | gas - 1,876,500 | | |
| 1000 | metal - 1,250,000 | 5,900,000 gal/yr | $3,260 |
| | gas - 4,650,000 | | |
| 3000 | metal - 3,700,000 | 17,650,300 gal/yr | $9,770 |
| | gas - 13,950,300 | | |
| 5000 | metal - 6,150,000 | 8,009,840 gal/yr | $32,560 |
| | gas - 23,250,600 | 29,400,600 | |

Change-Out Costs Molten Salt. Rockwell provided a refractory life estimate of 5 years. This results in refractory needing replaced once for the single site plant operating at 100 lb/hr and the collocated site operating at 1000 lb/hr.

The refractory cost was calculated for the rotary kiln at $28.74/ft$^2$ for 4-inch refractory. Due to higher operating temperatures, it is assumed that up to 8 inches will be used, resulting in a cost of

$$(28.74)(2)^{.6} = \$43.56/\text{ft}^2$$

at 100 lb/hr. One small unit 4 ft in diameter by an estimated 10 feet deep results in 130 ft$^2$ of refractory - $5,670.

1000 lb/hr. Two units, 8 ft diameter by 16 feet deep results in 810 ft$^2$ - $35,300.

| | | |
|---|---|---|
| 100 lb/hr. | (1st) | (2nd) |
| | Refractory16,690 | |
| | | 5,670 |
| Spare Parts (0.17)(98,140) | 16,690 | 16,690 |
| Materials/Supplies (0.17)(163,800) | 27,850 | 27,850 |
| | 44,540 | 50,210 |
| 400 lb/hr. | | |
| Refractory | 0 | 0 |
| Spare Parts (0.17)(239,470) | 40,710 | 40,710 |
| Materials/Supplies (0.17)(224,290) | 38,130 | 38,130 |
| | 78,840 | 78,840 |
| 1000 lb/hr SS. | (1st) | (2nd) |
| Spare Parts ((0.17)(470,660) | 80,010 | 80,010 |
| Materials/Supplies (0.17)(365,260) | 62,090 | 62,090 |
| | 142,100 | 142,100 |
| 1000 lb/hr CS. | | |
| Refractory | | 35,300 |
| Spare Parts (470,660) | 80,010 | 80,010 |
| Materials/Supplies (365,260) | 62,090 | 62,090 |
| | 142,100 | 177,400 |
| 3000 lb/hr. | | |
| Spare Parts (1,350,340) | 229,560 | 229,560 |
| Materials/Supplies (849,610) | 144,430 | 144,430 |
| | 373,990 | 373,990 |
| 5000 lb/hr. | | |
| Spare Parts (2,224,090) | 378,100 | 378,100 |
| Materials/Supplies (1,318,370) | 224,120 | 224,120 |
| | 602,220 | 602,220 |

The above labor and direct operating costs are summarized in Tables J-7 through J-10.

D. Development Costs

Development costs are presented in Table J-11.

E. Total Cost

Total costs are given in Tables J-12 through J-19 and Figure J-3 and J-4 present the life cycle cost curves. Total minimum life cycle cost for single site is $18 million and for collocated is $45 million.

F. Optimum Process Flow Rate

For single site the optimum process flow rate occurs around 400 lb/hr, based on total life cycle cost. For collocated site there was no topimum in the range covered. Lowest cost occurred at 1000 lb/hr. See Figures J-3 and J-4.

G. Operating Time

Operating times are given in Tables J-20 and J-21.

TABLE J-7. SINGLE SITE LABOR COSTS - MOLTEN SALT

| Area | Personnel Requirements (men/shift) Agent Rate 100 lb/hr | Agent Rate 400 lb/hr | Agent Rate 1000 lb/hr |
|---|---|---|---|
| Molten Salt Furnaces | 2 | 2 | 3 |
| Metal Handling | 1 | 1 | 1 |
| Salt Handling | 1 | 1 | 2 |
| Control Room | 1 | 1 | 1 |
| Pollution Abatement | 1 | 1 | 1 |
| Ultimate Disposal | 1 | 1 | 1 |
| Maintenance | 2 | 2 | 2 |
| Total/Shift | 9 | 9 | 11 |
| Man Years/Yr | 27 | 27 | 33 |
| Labor Cost $/Year at $50,000/man year | 1,350,000 | 1,350,000 | 1,650,000 |

TABLE J-8. SINGLE SITE OPERATION COSTS - MOLTEN SALT

| Utility | Annual Usage/Cost Agent Rate 100 lb/hr | Agent Rate 400 lb/hr | Agent Rate 1000 lb/hr |
|---|---|---|---|
| Water, $10^6$ gal/yr ($.53/1000 gal) | 0.61<br>325 | 2.38<br>1300 | 5.90<br>3260 |
| Electric, $10^6$ kwh/yr ($.05/kwh) | 0.6<br>30,000 | 2.4<br>120,000 | 6.0<br>300,000 |
| Fuel Oil, gal/yr ($1.20/gal) | 64,420<br>77,300 | 169,200<br>203,040 | 338,400<br>406,080 |
| Spare Parts, 6% Capital Equipment w/ Design | 98,140 | 239,470 | 470,660 |
| Oxygen, lb/hr (0.05¢/lb) | 750,000<br>37,500 | 3,000,000<br>150,000 | 7,500,000<br>375,000 |
| Salts, Ton/yr ($120/ton | 375<br>45,000 | 1,500<br>180,000 | 3,750<br>450,000 |
| Materials/Supplies 10% Other Operating | 163,800 | 224,290 | 365,260 |
| Total Direct Costs $/yr | 452,070 | 1,118,100 | 2,370,260 |

TABLE J-9. COLLOCATED SITE LABOR COSTS - MOLTEN SALT

| Area | Personnel Requirements (men/shift) Agent Rate 1000 lb/hr | Agent Rate 3000 lb/hr | Agent Rate 5000 lb/hr |
|---|---|---|---|
| Molten Salt Furnaces | 3 | 4 | 6 |
| Metal Handling | 1 | 2 | 2 |
| Salt Handling | 2 | 4 | 6 |
| Control Room | 1 | 1 | 1 |
| Pollution Abatement | 1 | 1 | 1 |
| Ultimate Disposal | 1 | 1 | 3 |
| Maintenance | 2 | 2 | 2 |
| Total/Shift | 11 | 17 | 22 |
| Man Years/Yr | 33 | 51 | 66 |
| Labor Cost $/Yr at $50,000/man years | 1,650,000 | 2,550,000 | 3,300,000 |

TABLE J-10. COLLOCATED SITE OPERATION COSTS - MOLTEN SALT

| Utility | Annual Usage/Cost | | |
|---|---|---|---|
| | Agent Rate 1000 lb/hr | Agent Rate 3000 lb/hr | Agent Rate 5000 lb/hr |
| Water, $10^6$ gal/yr<br>($.53/1000 gal) | 5.90<br>3,260 | 17.65<br>9,770 | 29.40<br>32,560 |
| Electric, $10^6$ kwh/yr<br>($.05/kwh) | 6.0<br>300,000 | 18.0<br>900,000 | 30.0<br>1,500,000 |
| Fuel Oil, gal/yr<br>($1.20/gal) | 338,400<br>406,080 | 1,015,200<br>1,218,240 | 1,692,000<br>2,030,400 |
| Spare Parts, 6% Capital Equipment w/ Design | 470,660 | 1,350,340 | 2,224,090 |
| Oxygen, lb/hr<br>(0.05¢/lb) | 7,500,000<br>375,000 | 22,500,000<br>1,125,000 | 37,500,000<br>1,875,000 |
| Salts, Ton/yr<br>($120/ton | 3,750<br>450,000 | 11,250<br>1,350,000 | 18,750<br>2,250,000 |
| Materials/Supplies 10% Other Operating | 365,260 | 849,610 | 1,318,370 |
| Total Direct Costs $/yr | 2,370,260 | 6,802,960 | 11,230,420 |

TABLE J-11. DEVELOPMENTAL COSTS - MOLTEN SALT

| | | |
|---|---|---|
| Phase II - Labor Studies | | |
| | Concept Refinement | $ 15,000 |
| | Refractory - Materials Compatibility Studies | 125,000 |
| | Environmental Studies | 100,000 |
| | Molten Salt Studies | 150,000 |
| | Molten Metal Studies | 150,000 |
| | Materials | 150,000 |
| | Subcontractors | 150,000 |
| | Contingency | 60,000 |
| | Preliminary Pilot Plant | 60,000 |
| | TOTAL PHASE II | $ 960,000 |
| Phase III | Conceptual Design | $ 250,000 |
| | Test Plan | 40,000 |
| | Pilot Plant | 1,070,000 |
| | Start-up | 173,300 |
| | Training | 454,700 |
| | Operating | 1,040,000 |
| | Development & Design Program | |
| | BCL | 1,000,000 |
| | A&E | 1,000,000 |
| | Subcontractors | 500,000 |
| | Other | 100,000 |
| | Subtotal | 5,628,000 |
| | Contingency (20%) | 1,125,600 |
| | TOTAL PHASE III | $6,753,600 |

TOTAL DEVELOPMENT COSTS - $7,713,600.

TABLE J-12. SINGLE SITE TOTAL OPERATING COST - MOLTEN SALT (100 LB/HR)

| Period | Labor Cost/Year | Other Direct Cost/Yr | Duration, Yr | Total Cost |
|---|---|---|---|---|
| Eq Acceptance | 450,000 | 150,690 | 0.50 | 300,305 |
| Training & Sys | 1,350,000 | 226,040 | 0.50 | 787,960 |
| A | 1,350,000 | 451,830 | 2.30 | 4,144,210 |
| Change Out | 1,350,000 | 44,540 | 0.17 | 274,040 |
| B/C | 1,350,000 | 451,830 | 3.08 | 5,549,040 |
| Change Out | 1,350,000 | 50,210 | 0.17 | 279,710 |
| D | 1,350,000 | 451,830 | 0.86 | 1,549,570 |
| Shutdown | 450,000 | 150,610 | 0.50 | 300,305 |
| Total Life Operating Cost | | | 8.08 | $13,185,740 |

TABLE J-13. SINGLE SITE TOTAL OPERATING COST - MOLTEN SALT (400 LB/HR)

| Period | Labor Cost/Year | Other Direct Cost/Yr | Duration, Yr | Total Cost |
|---|---|---|---|---|
| Eq Acceptance | 450,000 | 372,380 | 0.50 | 411,190 |
| Training & Sys | 1,350,000 | 558,580 | 0.50 | 954,290 |
| A | 1,350,000 | 1,117,150 | 0.57 | 1,406,280 |
| Change Out | 1,350,000 | 78,840 | 0.17 | 308,340 |
| B/C | 1,350,000 | 1,117,150 | 0.77 | 1,899,710 |
| Change Out | 1,350,000 | 78,840 | 0.17 | 308,340 |
| D | 1,350,000 | 1,117,150 | 0.24 | 592,120 |
| Shutdown | 450,000 | 372,380 | 0.50 | 411,190 |
| Total Life Operating Cost | | | 3.42 | $6,291,460 |

TABLE J-14. SINGLE SITE TOTAL OPERATING COST - MOLTEN SALT
(1000 LB/HR)

| Period | Labor Cost/Year | Other Direct Cost/Yr | Duration, Yr | Total Cost |
|---|---|---|---|---|
| Eq Acceptance | 550,000 | 789,290 | 0.50 | 669,645 |
| Training & Sys | 1,650,000 | 1,183,930 | 0.50 | 1,416,960 |
| A | 1,650,000 | 2,367,860 | 0.23 | 924,110 |
| Change Out | 1,650,000 | 142,100 | 0.17 | 422,600 |
| B/C | 1,650,000 | 2,367,860 | 0.31 | 1,245,540 |
| Change Out | 1,650,000 | 142,100 | 0.17 | 422,600 |
| D | 1,650,000 | 2,367,860 | 0.10 | 401,790 |
| Shutdown | 550,000 | 789,290 | 0.50 | 669,645 |
| Total Life Operating Cost | | | 2.48 | $6,172,890 |

TABLE J-15. SINGLE SITE COSTS - MOLTEN SALT

| | Agent Feed Rate | | |
|---|---|---|---|
| | 100 lb/hr | 400 lb/hr | 1000 lb/hr |
| Capital | $ 1,854,210 | $ 4,340,690 | $ 8,479,590 |
| Operating | 13,185,740 | 6,291,460 | 6,172,890 |
| Development | 7,713,600 | 7,713,600 | 7,713,600 |
| Total Life Cycle Cost | $22,750,000 | $18,350,000 | $22,350,000 |

TABLE J-16. COLLOCATED SITE TOTAL OPERATING COST - MOLTEN SALT (1000 LB/HR)

| Period | Labor Cost/Year | Other Direct Cost/Yr | Duration, Yr | Total Cost |
|---|---|---|---|---|
| Eq Acceptance | 550,000 | 789,290 | 0.50 | 669,645 |
| Training & Sys | 1,650,000 | 1,183,930 | 0.50 | 1,416,960 |
| A | 1,650,000 | 2,367,860 | 2.29 | 9,200,900 |
| Change Out | 1,650,000 | 142,100 | 0.17 | 422,600 |
| B/C | 1,650,000 | 1,267,860 | 3.06 | 12,375,010 |
| Change Out | 1,650,000 | 177,400 | 0.17 | 457,900 |
| D | 1,650,000 | 2,367,860 | 0.99 | 3,977,680 |
| Shutdown | 550,000 | 789,290 | 0.50 | 669,645 |
| Total Life Operating Cost | | | 8.20 | $29,190,340 |

TABLE J-17. COLLOCATED SITE TOTAL OPERATING COST - MOLTEN SALT (3000 LB/HR)

| Period | Labor Cost/Year | Other Direct Cost/Yr | Duration, Yr | Total Cost |
|---|---|---|---|---|
| Eq Acceptance | 850,000 | 2,265,250 | 0.50 | 1,557,625 |
| Training & Sys | 2,550,000 | 3,397,880 | 0.50 | 2,973,940 |
| A | 2,550,000 | 6,795,750 | 0.76 | 7,102,770 |
| Change Out | 2,550,000 | 373,990 | 0.17 | 807,490 |
| B/C | 2,550,000 | 6,795,750 | 1.03 | 9,626,120 |
| Change Out | 2,550,000 | 373,990 | 0.17 | 807,490 |
| D | 2,550,000 | 6,795,750 | 0.35 | 3,271,010 |
| Shutdown | 850,000 | 2,265,250 | 0.50 | 1,557,625 |
| Total Life Operating Cost | | | 3.98 | $27,704,070 |

TABLE J-18. COLLOCATED SITE TOTAL OPERATING COST - MOLTEN SALT (5000 LB/HR)

| Period | Labor Cost/Year | Other Direct Cost/Yr | Duration, Yr | Total Cost |
|---|---|---|---|---|
| Eq Acceptance | 1,100,000 | 3,734,040 | 0.50 | 2,417,020 |
| Training & Sys | 3,300,000 | 5,601,060 | 0.50 | 4,450,500 |
| A | 3,300,000 | 11,202,110 | 0.46 | 6,670,970 |
| Change Out | 3,300,000 | 602,220 | 0.17 | 1,163,220 |
| B/C | 3,300,000 | 11,202,110 | 0.61 | 8,846,290 |
| Change Out | 3,300,000 | 602,220 | 0.17 | 1,163,220 |
| D | 3,300,000 | 11,202,110 | 0.21 | 3,045,440 |
| Shutdown | 1,100,000 | 3,734,040 | 0.50 | 2,417,020 |
| Total Life Operating Cost | | | 3.12 | $30,173,710 |

TABLE J-19. COLLOCATED SITE COSTS - MOLTEN SALT

| | Agent Feed Rate | | |
|---|---|---|---|
| | 1000 lb/hr | 3000 lb/hr | 5000 lb/hr |
| Capital | $ 8,479,590 | $24,305,460 | $40,008,760 |
| Operating | 29,190,340 | 27,704,070 | 30,173,710 |
| Development | 7,713,600 | 7,713,600 | 7,713,600 |
| Total Life Cycle Cost | $45,400,000 | $59,700,000 | $77,900,000 |

FIGURE J-3

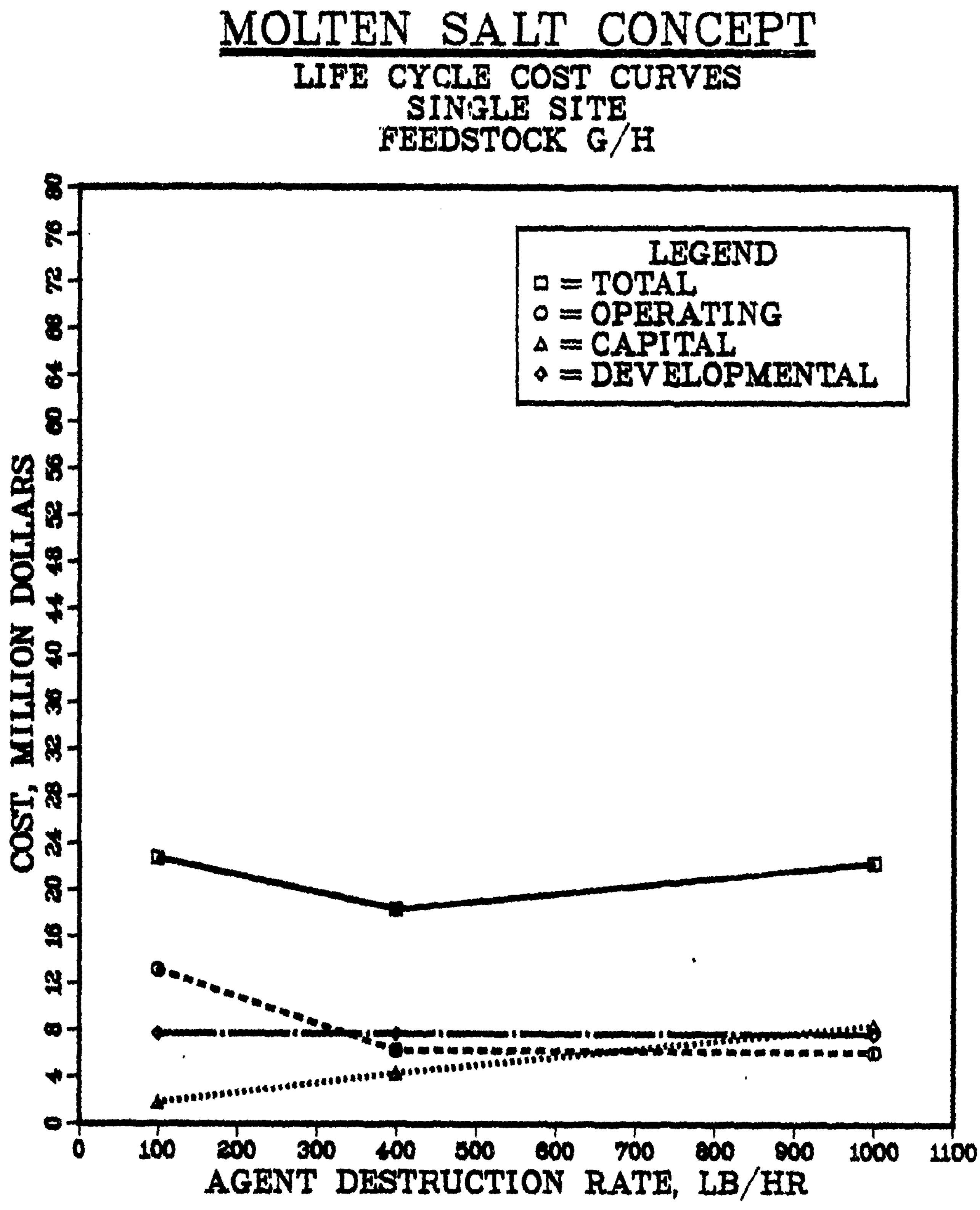

MOLTEN SALT CONCEPT
LIFE CYCLE COST CURVES
SINGLE SITE
FEEDSTOCK G/H
LEGEND
□ = TOTAL
○ = OPERATING
△ = CAPITAL
◇ = DEVELOPMENTAL
COST, MILLION DOLLARS
0 4 8 12 16 20 24 28 32 36 40 44 48 52 56 60 64 68 72 76 80
0 100 200 300 400 500 600 700 800 900 1000 1100
AGENT DESTRUCTION RATE, LB/HR

FIGURE J-4

# MOLTEN SALT CONCEPT

## LIFE CYCLE COST CURVES
## COLLOCATED SITE
## FEEDSTOCK G/H

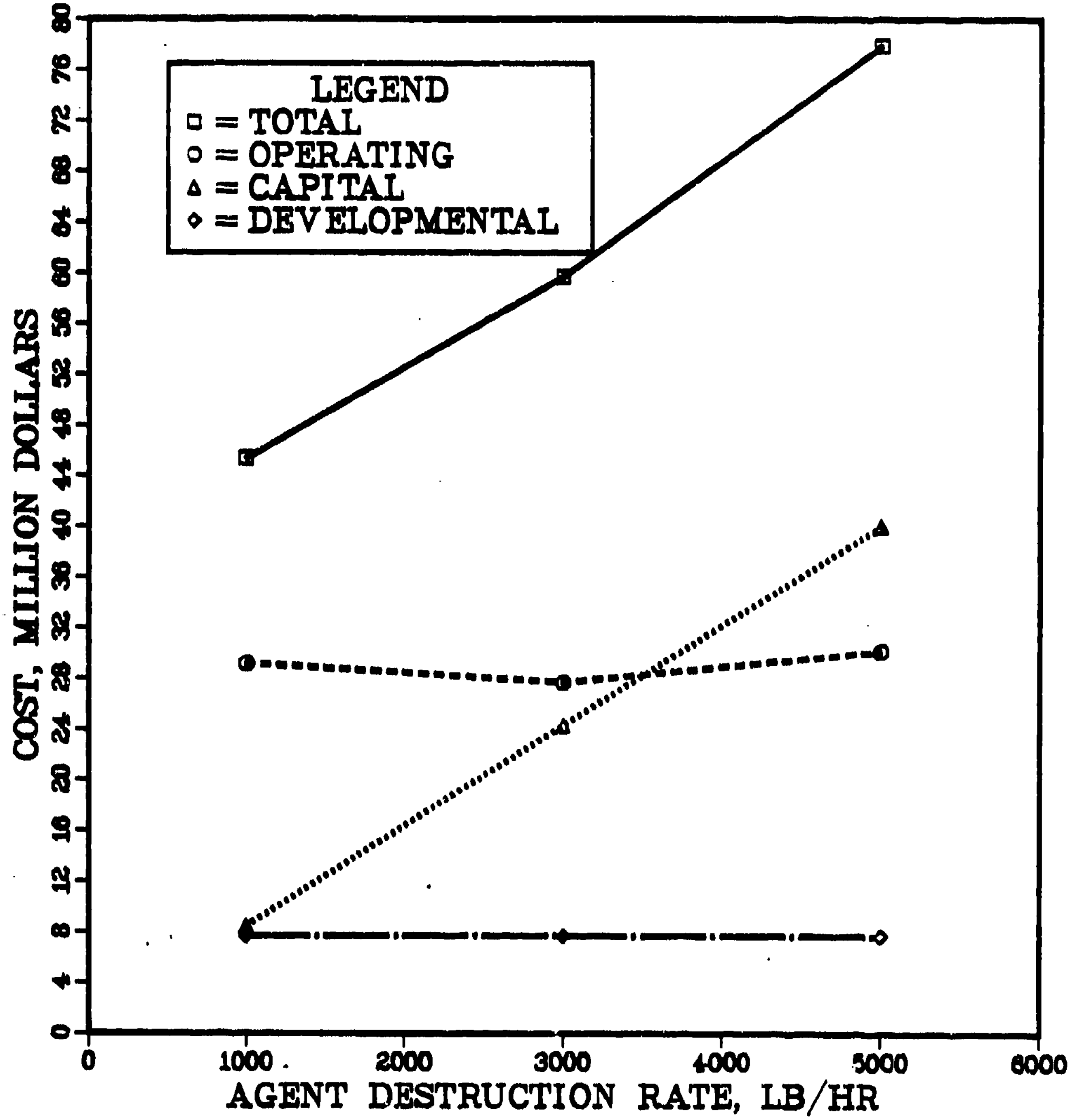


TABLE J-20. COLLOCATED SITE OPERATING TIME - MOLTEN SALT

| Munition Category | Munition Type | Inventory | Through-put Per Hour 1000 lb/hr | Through-put Per Hour 3000 lb/hr | Through-put Per Hour 5000 lb/hr | System Availability | Production Years 1000 lb/hr | Production Years 3000 lb/hr | Production Years 5000 lb/hr |
|---|---|---|---|---|---|---|---|---|---|
| A | M55 Rockets | 800,000 | 93.5 | 280.4 | 467.3 | 0.928 | 1.84 | 0.61 | 0.37 |
| | M23 Mines | 200,000 | 95.2 | 285.7 | 476.2 | 0.928 | 0.45 | 0.15 | 0.09 |
| B/C | Mortars | 500,000 | 166.7 | 500.0 | 833.3 | 0.928 | 0.65 | 0.22 | 0.13 |
| | 105 mm Projectiles | 500,000 | 625.0 | 1875.0 | 3125.0 | 0.928 | 0.17 | 0.06 | 0.03 |
| | 155 mm Projectiles | 500,000 | 153.8 | 465.5 | 769.2 | 0.928 | 0.70 | 0.23 | 0.14 |
| | 8" Projectiles | 500,000 | 69.0 | 206.9 | 344.8 | 0.928 | 1.56 | 0.52 | 0.31 |
| D | Bombs | 8,000 | 4.6 | 13.6 | 22.7 | 0.928 | 0.37 | 0.13 | 0.08 |
| | Ton Containers/ Spray Tanks | 2,000 | 0.7 | 2.0 | 3.3 | 0.928 | 0.62 | 0.22 | 0.13 |

TABLE J-21. SINGLE SITE OPERATING TIME - MOLTEN SALT

| Munition Category | Munition Type | Inventory | Through-put Per Hour 100 lb/hr | 400 lb/hr | 1000 lb/hr | System Availability | Production Years 100 lb/hr | 400 lb/hr | 1000 lb/hr |
|---|---|---|---|---|---|---|---|---|---|
| A | M55 Rockets | 80,000 | 9.3 | 37.4 | 93.5 | 0.928 | 1.85 | 0.46 | 0.18 |
| | M23 Mines | 20,000 | 9.5 | 38.1 | 95.2 | 0.928 | 0.45 | 0.11 | 0.05 |
| B/C | Mortars | 50,000 | 16.7 | 66.7 | 166.7 | 0.928 | 0.65 | 0.16 | 0.06 |
| | 105 mm Projectiles | 50,000 | 62.5 | 250.0 | 625.0 | 0.928 | 0.17 | 0.04 | 0.02 |
| | 155 mm Projectiles | 50,000 | 15.4 | 61.5 | 153.8 | 0.928 | 0.70 | 0.18 | 0.07 |
| | 8" Projectiles | 50,000 | 6.9 | 27.6 | 69.0 | 0.928 | 1.56 | 0.39 | 0.16 |
| D | Bombs | 800 | 0.4 | 1.8 | 4.6 | 0.928 | 0.43 | 0.10 | 0.04 |
| | Ton Containers/ Spray Tanks | 200 | 0.1 | 0.3 | 0.7 | 0.928 | 0.43 | 0.14 | 0.06 |

APPENDIX K

ENGINEERING AND ECONOMIC ANALYSIS - UNDERGROUND DETONATION

APPENDIX K

# ENGINEERING AND ECONOMIC ANALYSIS - UNDERGROUND DETONATION

## Engineering Analysis

### A. System Concept Description

The underground detonation concept is a collocated operation designed to destroy the entire lethal agent inventory with one underground detonation of 70 Kilotons (KT) of conventional high explosives and pyrotechnics. The first stage for successful implementation of the concept would be selection of a site which meets the following geological criteria:

- The host rock must contain the explosion and explosion residues
- Areas with major aquifers must be avoided
- Tectonically unstable areas must be avoided
- No valuable minerals (e.g., ores or oil reserves) can be contained within the site.

In addition, since the detonation will produce a shock wave severe enough to cause structure damage on the surface and may create a subsidence crater, the site must be geographically located in a zone of low population density. Once a site has been selected, the preliminary conceptual design of the facility requires that shafts be sunk to a depth of 2,000 ft and a destruction cavity mined out of salt, granite, or basalt. The cavity is sized such that it will hold the entire agent inventory, conventional high explosives, and pyrotechnics. Following the emplacement of the materials, the shafts will be backfilled and sealed and the explosives detonated to destroy the inventory.

Surface facilities will be located directly above the cavity and will serve to receive, inspect, and transfer the munitions,

explosives, and pyrotechnics to the mined cavity. All surface facilities will be decommissioned and salvaged prior to detonation.

The underground detonation facility will have the following subsurface facilities, shafts, and surface facilities.

Surface Facilities. To support the activities of mining and loading the destruction cavity, the following surface facilities are required:

- Men and materials buildings to provide services for crews and mined materials movement.
- Ventilation supply and exhaust buildings to provide air to cavity and filter the exhaust air.
- Support service buildings for maintanence, wharehousing, and utilities.
- Mined material storage to minimize environmental impact of mining activities - material used to infill subsidence crater (if one develops)
- Buildings to receive, inspect, and transfer materials to the mine shaft.

Shafts. The following shafts must be sunk to the geological formation in which the cavity will be excavated in order to provide for ventilation and to permit the flow of men and materials to the cavity.

- Men and materials (small) access to cavity shafts, 10 ft diameter.
- Munition, high explosives, pyrotechnic shafts, 14 to 32 ft diameter.
- Mined cavity ventilation shaft, 10 ft diameter.
- Mined materials transport shaft and ventilation exhaust, 14-32 ft diameter.

<u>Subsurface Facilities</u>. The concept requires that the following facilities be constructed in the selected geological formation.

- The destruction cavity
- Personnel and maintenance area
- Shaft underground facilities
- Utilities
- Materials handling equipment.

As previously mentioned, the destruction cavity must be large enough to contain the entire inventory and the needed energetic material. It is estimated that 70 KT of energetic material is required to rupture the munition cavities and provide sufficient temperature for successful agent destruction. These are categorized as follows:

- 10 KT H.E. as follows:
  - H.E. in promilitarized inventory, 2,824 tons
  - TNT, 7,176 tons to rupture or detonate the munition/items
- 60 KT pyrotechnics to provide heat
  - Ammonium Nitrate as an oxidizer
  - No. 2 fuel oil as a heat source.

Destruction Cavity. The size of cavity required to contain the inventory, the high explosives, and the pyrotechnic composition was estimated as follows:

| <u>Quantities Required:</u> | |
|---|---|
| H. E. | 7,176 tons |
| Pyrotechnic | |
| 94.4% Ammonium Nitrate | 56,640 tons |
| 5.6% No. 2 fuel oil | 3,360 tons |

Volumes of High Explosives and Pyrotechnics:

Ammonium Nitrate, = 1.725 g/cc

56,640 tons = $1.13 \times 10^8$ lb x $\frac{1}{107 \text{ lbs/ft3}}$

= $1.06 \times 10^6$ $ft^3$ Ammonium Nitrate

+ 25% factor

Volume of Ammonium Nitrate = $\underline{1.32 \times 10^6 \ ft^3}$

No. 2 fuel oil

$6.72 \times 10^6$ lbs x $\frac{1}{58.81 \ lb/ft^3}$

= $1.25 \times 10^5$ $ft^3$

+ 25% factor

Volume of No. 2 fuel oil = $\underline{1.56 \times 10^5 \ ft^3}$

Volume of High Explosives

TNT, = 1.56 g/cc

7,176 tons = $1.43 \times 10^7$ lbs x $\frac{1}{97.31 \ lbs/ft^3}$

= $1.47 \times 10^5$ $ft^3$

+ 25% factor

Volume of H.E. = $\underline{1.84 \times 10^5 \ ft^3}$

Volume of Cavity Required

| | | |
|---|---|---|
| Munitions Volume | = | $3.53 \times 10^6$ $ft^3$ |
| High Explosives | = | $1.84 \times 10^5$ $ft^3$ |
| No. 2 fuel oil | = | $1.56 \times 10^5$ $ft^3$ |
| Ammonium Nitrate | = | $\underline{1.32 \times 10^6 \ ft^3}$ |
| subtotal | = | $5.19 \times 10^6$ $ft^3$ |
| + 25% factor | = | $1.3 \times 10^6$ $ft^3$ |
| Total | = | $\underline{6.49 \times 10^6 \ ft^3}$ |

## B. System Feed Requirements

The concept is designed to process the entire inventory in feedstock configuration a. The inventory items can be processed in an as-stored condition eliminating the need for mechanical preparation.

## C. Pollution Abatement System

While no effluents are expected from this concept, an extensive study of the environmental impact would be required. A review of the socio-economic impact should also be considered.

## D. Ultimate Disposal

All waste products are retained in the detonation cavity and are 5X decontaminated. Suitable containment characteristics are a requirement of the selection of the appropriate geological formation.

## E. System Concept Advantages

The concept offers the following advantages;

- No mechanical preparation is required
- No flue gas cleanup is required
- Provides the most effective ultimate disposal scenario.

## F. System Concept Disadvantages

- It is politically sensitive
  - Public unwillingness to have program conducted in their region
- Testing and modeling is extremely difficult
- It is geologically site specific.

## G. System Concept Knowledge Gaps

The major unknowns in this concept are as follows:

- The quantity and type of high explosives required to ensure destruction of all agent
- How the explosives must be placed to ensure rupture of all munition bodies
- The magnitude of the shock wave.

## H. Safety

A number of very serious safety concerns are present in this concept. Successful implementation would require this to be the largest planned, non-nuclear explosion in history. It would also require the entire lethal agent inventory to be on a single site at one time. The accident scenarios associated with these two facts, although solvable, are expected to have a major impact on the concept economics. A more difficult safety consideration revolves around recovery from an unsuccessful operation. Recovery from such a situation would prove very difficult, if not impossible.

## I. Likelihood of Development

In the preliminary evaluation, this concept was believed to be developable within five years. However, due to the knowledge gaps and political considerations identified in the engineering evaluation, it is now anticipated that this concept would take at least 10 years to develop. For this reason, the engineering evaluation was terminated at this point and cost estimation begun.

## Economic Evaluation

### A. Facility Costs

The requirements of the underground detonation conceptual design and those of a mined geologic nuclear waste repository are very similar. Both are basically cavities mined 2000 ft deep within the earth and the host rock must be groundwater free and have excellent containment characteristics. The primary differences between the two concepts are:

(1) Nuclear waste repository is much larger
 (a) 2,000 acres vs 9.95 acres
(2) Basic purposes
 (a) Nuclear waste storage vs destroying agent inventory with underground explosion.

Since the facilities required and the construction costs incurred are similar, staff members of the Office of Nuclear Waste Isolation were consulted and cost estimate documents were review[1,2,3,4]. The estimated costs of construction and facilities included in this review are therefore, based on estimated costs of geologic nuclear waste repositories.

Shaft Emplacement and Surface Facility Costs. Costs for shaft emplacement are based on the following assumptions:

- Geologic conditions are ideal
- No special engineering problems encountered.

It must be further noted that the depth of the cavity (2000 ft) and the host rock types cited (salt, granite, basalt) in this review were chosen for cost estimation purposes only. These are the depths and host rock media chosen for the mined geologic nuclear waste repository concept. However, the rock types suited for nuclear waste storage have many of the characteristics required for underground detonation. Also, a cursory review of the effects of underground nuclear explosive devices detonated in granite, dolomite, and zeolitized tuff (Project Plowshare[6,7]), reveals that salt, granite, and

basalt may possibly contain a 70 KT explosion. The scaled depth of burial for the underground detonation of 70 KT at 2000 ft is 485 ft.* This scaled-depth-of-burial number indicates that the explosion would probably be contained. Further research is required to obtain the required information.

Contractor costs estimates for the construction of the facility include a 50 percent cost factor and were broken down as follows:

(1) 25 percent allowance of anticipated construction costs that would be detailed with further planning
(2) [illegible] percent overhead and administration
(3) [illegible] percent profit and risk for contractor

NOTE: Land and land rights is not factored by 50 percent.

On the basis described above, the $217M cost estimate for shaft emplacement and surface facilities shown in Table K-1 was produced. Although many items remain to be costed, the sum of the partial costs that were estimated and are discussed below was great enough to indicate that more comprehensive costing was not necessary.

Destruction Cavity Costs. The costs estimated for cavity excavation could not be based on the actual material being mined. Estimation of the excavation costs were, therefore, based on the cost of mining granite at 1500 ft.[5] Since the cost of mining salt costs less than granite and mining basalt costs more than mining granite, this is anticipated to be a median estimate. On this basis, the costs of excavating the destruction cavity were estimated to be $46M.

The shaft emplacement and surface facility costs ($217M) combined with the cavity excavation costs ($46M) bring the estimated total facility costs to $263M.

*Scaled-depth-of-burial is a means of comparing underground nuclear tests of different yields emplaced at different depths. This is the depth for an equivalent 1 KT detonation.

TABLE K-1. ITEMIZED FACILITY COST

| Item | Cost ($\$ \times 10^6$) |
| --- | --- |
| Land & Land Rights | 13.255 |
| Drill String & Geophysical Survey | 14.325 |
| Drill Rig Including Hole Survey | 7.050 |
| General Site Work | 42.932 |
| Mine Development - Area Ventilation | 1.583 |
| Holding Pond | 2.044 |
| Mine Waste Storage | 13.249 |
| Cavity Excavation | 46.213 |
| Shafts (2) 10 ft Dia. | 50.096 |
| Shafts (2) 14 ft - 32 ft Dia. | 72.00 |
| Engineering Lab | 0.600 |
| TOTAL | 263.347 |

## B. Capital Costs

Little capital equipment would be required for this concept and no estimation of these items was made. Equipment that would be required would include:

- Fork trucks and other materials handling equipment
- Air compressors to supply air to the underground cavity
- Air conditioning for the underground facility.

## C. Operating Costs

The only operating costs estimated were those for the cost of explosives and pyrotechnics. These are as follows:

- High Explosives:
  7,176 tons x $2,880[8]/ton = $20,666,880
- Ammonium Nitrate
  56, 640 tons x $145[9]/ton = $ 8,212,800
- No. 2 Fuel Oil
  932,038 gallons x $1.20[10]/gal = $ 1,118,447
  Total Estimated Materials Cost = $29,998,000

Additional operating costs which were not estimated would include:

- Labor for filling the cavity with the inventory and the required explosives
- Shaft backfilling and sealing
- Testing to certify agent destruction
- Decommisioning and removal of surface structures.

It is anticipated that the costs of these listed items would be high.

D. Development Costs

Implementation of this concent could only be accomplished by conducting an extensive development program. Some of the tasks of this program would be

- Engineering studies to determine:
  - Acceptable rock media for detonation and containment of explosion residues
  - Required depth of burial
  - Chemistry of explosion residues
  - Process modeling and testing
- Agent destruction proof tests
- Site selection and exploration
- Development of recovery methods for process failures
- Public relations and political lobbying.

While comprehensive costs for this development effort were not produced, site selection and exploration has the potential to overwhelm the other costs. On-site characterization of any candidate site selected by the known geology of the region requires that a number of 6 inch diameter holes be drilled to a depth of 3000-4000 feet. Each of these test holes cost $1 million to $5 million depending on the geologic conditions. If the site still looks promising, a 10 ft diameter shaft is sunk to a depth of 2000 feet at a cost of $24 million. Horizontal geophysical studies would then be conducted at a cost of $7 million bringing the costs for evaluating a single site to at least $37 million. If at any point a site is found unacceptable, the on-site characterization process would have to be repeated at another site.

A further indication of the magnitude of these costs can be found in the fact that the Office of Nuclear Waste Isolation, while looking at salt only as the host rock, spends approximately $32 million per year on site selection and exploration. It is therefore estimated that the development costs would be at least $50M and could be $200M or more.

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# APPENDIX L
# RAM ANALYSIS

## APPENDIX L

## RAM ANALYSIS

System availability for the various demilitarization system concepts was estimated from the availability of the components making up the system. Two major sources of component availability were used: (1) the government-Industry Data Exchange Program[L-1], and (2) "Equipment Availability Fossil Component Cause Code Summary Report, 1973", EEI Publication No. 74-57[L-2]. A number of other possible sources were examined[L-3-5] but were rejected because the information was not usable in the form presented (e.g., probability of operation on demand or mean time between failures without an associated mean time to repair) or because the availabilities seemed unrealistically high, or a combination of these factors. For system components for which no appropriate data were found, engineering estimates were made based on the failure considered most likely and the estimated time to repair. Table L-1 presents the basic component availabilities used to estimate the system availabilities. For applications that were considered significantly more severe than those pertaining to the data base, the basic unavailability was multiplied by a factor of two or four. Where a choice of values was available for similar components, the less favorable (higher) unavailability was chosen. Reported or estimated MTTR or unavailability was doubled where the repair would require the maintenance personnel to wear DPEs.

The power plant component availability data of Reference L-2 was adjusted to an operating hour basis and averaged for all plant size categories. It should be noted that these data are largely on a per-plant basis, and may include several parallel devices. No information is available to correct for this effect, if and where present.

System availabilities were calculated from the component availabilities assuming no common failures and no redundancy. Failure of any one of paralleled components was assumed to force system shutdown.

Tables L-2 through L-6 present the availability calculations for the four selected demilitarization processes. For the Acid Roaster process, the calculated availabilities are for full plant capacity. The availability

of partial capacity ranges from slightly greater than for full capacity to significantly greater than for full capacity depending on process capacity.

TABLE L-1. COMPONENT UNAVAILABILITY

| Component | MTBF[1] | MTTR[1] | $UA \times 10^5$ [1] | Source[2] |
|---|---|---|---|---|
| Air lock door | 5405 | 6.8 | 126 | A |
| Hydraulic cylinder | 3425 | 5.2 | 152 | A |
| Hydraulic power supply | 3408 | 7.5 | 220 | A |
| Conveyor | 1000 | 3.6 | 360 | A |
| Feeder(3) | 1000 | 3.6 | 360 | - |
| Elevator(3) | 1000 | 3.6 | 360 | - |
| Hydraulic motor | 2857 | 10 | 350 | C |
| Scrap chute | 6000 | 3 | 50 | C |
| Heat exchanger | - | - | 80 | B |
| Instrument, temperature, pressure, level, flow | 6061 | 2.8 | 46 | A |
| Fan, blower | - | - | 48 | B |
| Fuel supply | - | - | 7 | B |
| Burner[4] | 365 | 2 | 594 | C |
| Refractory[5] | 8760 | 200 | 2283 | C |
| Spray drier[6] | 168 | 4 | 2381 | C |
| Bag house[7] | 730 | 2 | 274 | C |
| Plasma jet head | - | - | 1000 | D |
| Electrical power supply | - | - | 100 | C |
| Induction heater coil | - | - | 10 | C |
| Metal tap | - | - | 500 | C |
| Slag tap | - | - | 500 | C |
| Quench tower[8] | - | - | 1190 | C |
| Pump | - | - | 20 | B |
| Valves and piping | - | - | 25 | B |
| Duct, stack | - | - | 8 | B |
| Switch gear | - | - | 12 | B |
| Central control | - | - | 746 | - |
| Controller | (5000) | (2.8) | (56) | A |
| Display | (463) | (3.2) | (690) | A |
| Room, doors | - | - | 200 | C |

NOTES:

1. MTBF = Mean Time Between Failures: MTTR - Mean Time to Repair: UA = unavailability, hr/hr.

2. A, Reference (L-1): B, Reference (L-2): C, Engineering estimate: D, Quote from Westinghouse Electric Company

3. Assumed to be the same as conveyors.

4. Most probable failure is failure of flame detector. MTBF of 365 hr, MTTR (replace detector or clean optics) of 2 hrs plus an additional 4 hr per year.

5. Severe duty, replacement once per year, 10 days, 20 hrs per day repair time.

6. Most probable failure is nozzle plugging. MTBF is 168 hr, MTTR (replace nozzles) is 4 hr.

7. Most probable failure is bag failure. MTBF is 730 hr MTTR (replace one bag) is 2 hr.

8. Quench tower UA taken as 1/2 the UA of a spray drier.

TABLE L-2. AVAILABILITY OF THE ROTARY KILN SYSTEM

| Equipment Item | No. in System | Unavailability, hr/hrx10[5]: Equipment Item | Unavailability, hr/hrx10[5]: System |
|---|---|---|---|
| **Kiln** | | | |
| Elevator | 1 | 720[1] | 720 |
| Ram feeder | 1 | 360 | 360 |
| Ram | 1 | 152 | 152 |
| Burner | 1 | 594 | 594 |
| Combustion air fan | 1 | 48 | 48 |
| Fuel supply | 1 | 14[2] | 14 |
| Seal air fan | 1 | 48 | 48 |
| Locks | 1 | 152 | 152 |
| Instrumentation | 6 | 46 | 276 |
| Refractory | 1 | 4566[3] | 4566 |
| Rotation system | 1 | 135 | 135 |
| **Afterburner** | | | |
| Burner | 1 | 594 | 594 |
| Combustion air fan | 1 | 48 | 48 |
| Scrap discharge conveyor | 1 | 720[4] | 720 |
| Scrap discharge chute | 1 | 50 | 50 |
| Fuel supply | 1 | 14[2] | 14 |
| Pump | 1 | 20 | 20 |
| Instrumentation | 4 | 46 | 184 |
| Duct | 1 | 8 | 8 |
| Refractory | -- | -- | --[5] |
| **Scrubber** | | | |
| Spray Drier | 1 | 2381 | 2381 |
| Pump | 2 | 40[6] | 80 |
| Discharge Conveyor | 1 | 360 | 360 |
| Valves and piping | 2 | 50[7] | 100 |
| Chemical feeder | 1 | 360 | 360 |
| Instrumentation | 6 | 46 | 276 |
| Duct | 1 | 8 | 8 |
| **Bag House** | | | |
| Bag house | 1 | 274 | 274 |
| Discharge conveyor | 1 | 360 | 360 |
| ID fan | 1 | 48 | 48 |
| Duct, stack | 1 | 8 | 8 |
| **General** | | | |
| Switch gear | 1 | 12 | 12 |
| Central control | 1 | 746 | 746 |
| Hydraulic power | 1 | 220 | 220 |
| Room, doors | -- | 200 | 200 |
| Total System Unavailability | | | $14{,}136 \times 10^{-5}$ |

Total System Availability = 1 -0.141 = 0.859[8]

NOTES:

1. Value for conveyor x 2 for more complex operation.
2. Power plant value x 2: power plant value considered unrealistically low.
3. Nominal value x 2 for severe mechanical service.
4. Nominal value x 2 for severe service.
5. Included with refractory in kiln.
6. Nominal value x 2 for severe service (chemical solution).
7. Nominal value x 2 for severe service (chemical solution).
8. For feedstock h, this value becomes 0.881, as a result of reduced severity of refractory service (see Note 3).

TABLE L-3. AVAILABILITY OF THE FLUIDIZED BED SYSTEM

| Equipment Item | No. in System | Unavailability, hr/hrx10[5] Equipment Item | System |
|---|---|---|---|
| **Fluidized Bed** | | | |
| Ram feeder | 1 | 360 | 360 |
| Ram | 1 | 152 | 152 |
| Burner | 1 | 594 | 594 |
| Fuel supply | 1 | 14[1] | 14 |
| Combustion air fan | 1 | 48 | 48 |
| Locks | 2 | 152 | 304 |
| Bed make-up system | 1 | 360[2] | 360 |
| Bed recycle system | 1 | 360[2] | 360 |
| Discharge system | 1 | 1440[3] | 1440 |
| Ram | 1 | 152 | 152 |
| Scrap separator | 1 | 720[4] | 720 |
| Scrap chute | 1 | 50 | 50 |
| Instrumentation | 8 | 46 | 368 |
| Fuel supply | 1 | 14[5] | 14 |
| Pneumatic transport fan | 1 | 48 | 48 |
| Duct | 1 | 8 | 8 |
| Refractory | 1 | 2283 | 2283 |
| **Afterburner** | | | |
| Burner | 1 | 594 | 594 |
| Combustion air fan | 1 | 48 | 48 |
| Fuel supply | 1 | 14[1] | 14 |
| Instrumentation | 4 | 46 | 184 |
| Duct | 1 | 8 | 8 |
| Refractory | -- | -- | --[5] |
| **Scrubber** | | | |
| Spray drier | 1 | 2381 | 2381 |
| Pump | 2 | 40[6] | 80 |
| Discharge conveyor | 1 | 360 | 360 |
| Valves and piping | 2 | 50[7] | 100 |
| Instrumentation | 6 | 46 | 276 |
| Chemical feeder | 1 | 360 | 360 |
| Duct | 1 | 8 | 8 |
| **Bag House** | | | |
| Bag house | 1 | 274 | 274 |
| Discharge conveyor | 1 | 360 | 360 |
| ID fan | 1 | 48 | 48 |
| Duct, stack | 1 | 8 | 8 |
| **General** | | | |
| Switch gear | 1 | 12 | 12 |
| Central control | 1 | 746 | 746 |
| Hydraulic power | 1 | 220 | 220 |
| Room, doors | -- | 200 | 200 |
| Total System Unavailability | | | $13{,}404 \times 10^{-5}$ |
| Total System Availability | = 1 - 0.134 = 0.866 | | |

NOTES:

1. Nominal value x 2. Nominal value for power plants considered unrealistically low.
2. Considered equivalent to a conveyor.
3. Value for conveyor x 4 for severe service.
4. Value for conveyor x 2 for severe service.
5. Included with refractory in fluidized bed.
6. Nominal value x 2 for severe service (chemical solution).
7. Nominal value x 2 for severe service (chemical solution).

TABLE L-4. AVAILABILITY OF THE PLASMA/MOLTEN METAL PROCESS[1]

| Equipment Item | No. in System | Unavailability, hr/hrx10[5] Equipment Item | System |
|---|---|---|---|
| **Plasma Furnace** | | | |
| Input conveyor | 1 | 360 | 360 |
| Chamber conveyor | 1 | 720[2] | 720 |
| Locks | 2 | 152 | 304 |
| Plasma gun | 1 | 1000 | 1000 |
| Plasma power supply | 1 | 100 | 100 |
| Induction heater coil | 1 | 10 | 10 |
| Induction heater power supply | 1 | 100 | 100 |
| Air supply fan | 1 | 48 | 48 |
| Refractory | 1 | 1000[3] | 1000 |
| Slag tap and disposal | 1 | 500 | 500 |
| Metal tap and disposal | 1 | 500 | 500 |
| Instrumentation | 12 | 46 | 552 |
| Duct | 1 | 8 | 8 |
| **Scrubber[4]** | | | |
| Scrubber tower | 1 | 2381[5] | 2381 |
| Pump | 2 | 40[6] | 80 |
| Valves and piping | 2 | 50[7] | 100 |
| Chemical feeder | 1 | 360 | 360 |
| Instrumentation | 6 | 46 | 276 |
| Duct | 1 | 8 | 8 |
| **Afterburner** (Pyrolysis Products Burner) | | | |
| Burner | 1 | 594 | 594 |
| Combustion air fan | 1 | 48 | 48 |
| Fuel supply | 1 | 14[8] | 14 |
| Instrumentation | 4 | 46 | 184 |
| Refractory | 1 | 1182[9] | 1182 |
| Duct | 1 | 8 | 8 |
| **Quench Tower** | | | |
| Quench tower | 1 | 1165[10] | 1165 |
| Pump | 2 | 20 | 40 |
| Valves and piping | 2 | 25 | 50 |
| Instrumentation | 6 | 46 | 276 |
| Duct | 1 | 8 | 8 |
| **Bag House** | | | |
| Bag house | 1 | 274 | 274 |
| Discharge conveyor | 1 | 360 | 360 |
| ID fan | 1 | 48 | 48 |
| Duct, stack | 1 | 8 | 8 |
| **General** | | | |
| Switch gear | 1 | 12 | 12 |
| Central control | 1 | 746 | 746 |
| Hydraulic power | 1 | 220 | 220 |
| Room, doors | - | 200 | 200 |
| Total System Unavailability | | | $13,844 \times 10^{-5}$ |
| Total System Availability = 1-0.138 = 0.862 | | | |

TABLE L-4 (continued)

NOTES:

1. This assessment was made for a process configuration involving scrubbing of pyrolysis products with molten salt prior to pyrolysis product incineration. Other process configurations are being considered.
2. Nominal value x 2 for severe service (hot environment).
3. The vendor quotes a planned unavailability of about 1000-2000x$10^{-5}$ hr/hr for refractory repair. A value of 1000x$10^{-5}$ for unplanned unavailability has been adopted as a reasonable estimate.
4. The molten salt scrubber is not well defined at this time. In the absence of other information, it has been treated essentially as a spray drier scrubber.
5. Value for a spray drier scrubber.
6. Nominal value x 2 for severe service (chemical solution).
7. Nominal value x 2 for severe service (chemical solution).
8. Nominal value x 2. Nominal value for power plants considered unrealistically low.
9. Nominal value x 1/2 for less severe duty (pollutants removed upstream).
10. Nominal value for spray drier scrubber x 1/2 for less severe duty (clean water feed).

TABLE L-5. ACID ROASTER SYSTEM, 400 LB/HR

| Equipment Item | No. in System | Unavailability, hr/hr$\times10^5$ Equipment Item | System |
|---|---|---|---|
| **Dissolution Chamber** | | | |
| Munitions loader | 3 | 360[1] | 1080 |
| Dissolution chamber | 3 | 100[2] | 300 |
| Chamber closure | 3 | 152 | 456 |
| Vent fan | 1 | 96[3] | 96 |
| Dissolution pumps | 3[4] | 40[5] | 120 |
| Acid cooler | 3 | 160[6] | 480 |
| Valves and piping | 3 | 50[7] | 150 |
| Duct | 3 | 16[8] | 48 |
| Chamber unloader | 3 | 360[1] | 1080 |
| Instrumentation | 18 | 46 | 828 |
| **Roaster/Afterburner** | | | |
| Burner | 2 | 594 | 1188 |
| Combustion air blower | 2 | 48 | 96 |
| Fuel supply | 2 | 14[9] | 28 |
| Spray nozzles | 1 set | 2381 | 2381 |
| Refractory | 1 | 1141[10] | 1141 |
| Solids discharge | 1 | 360 | 360 |
| Roaster feed pumps | 1 | 40[5] | 40 |
| Cyclone | 1 | 360[11] | 360 |
| Oxide blower | 1 | 48 | 48 |
| Duct | 1 | 16[8] | 16 |
| Instrumentation | 8 | 46 | 368 |
| **Acid Regeneration** | | | |
| Cyclone gas cooler | 2 | 160[6] | 320 |
| Isothermal absorber | 1 | 1190[12] | 1190 |
| Bottoms pump | 1[4] | 40[5] | 40 |
| Cooler | 1 | 160[6] | 160 |
| Acid makeup pump | 1[4] | 40[5] | 40 |
| Adiabatic absorber | 1 | 1190[2] | 1190 |
| Cooler | 1 | 160[6] | 160 |
| Valve and piping | 4 | 50 | 200 |
| Duct | 1 | 16[8] | 16 |
| Instrumentation | 11 | 46 | 506 |
| **Pollution Control** | | | |
| Dry scrubber preheater | 1 | 80 | 80 |
| Dry scrubber | 1 | 2381 | 2381 |
| Discharge conveyor | 1 | 360 | 360 |
| Chemical feeder | 1 | 360 | 360 |
| Pump | 2 | 40[12] | 80 |
| Valves and piping | 2 | 50[7] | 100 |
| Duct | 1 | 8 | 8 |
| Bag house | 1 | 274 | 274 |
| Discharge conveyor | 1 | 360 | 360 |
| Duct, stack | 1 | 8 | 8 |
| ID fan | 1 | 48 | 48 |
| Instrumentation | 6 | 46 | 276 |

TABLE L-5. (continued)



| Equipment Item | No. in System | Unavailability, hr/hrx10[5] Equipment Item | System |
|---|---|---|---|
| **General** | | | |
| Switch gear | 1 | 12 | 12 |
| Hydraulic power | 1 | 220 | 220 |
| Central control | 1 | 746 | 746 |
| Cooling tower | 1 | 595[13] | 595 |
| Cooling water pump | 1 | 48 | 48 |
| Room, doors | 2 | 200 | 400 |
| Total System Unavailability | | | $20,842 \times 10^{-5}$ |
| Total System Availability = 1 -0.208 = .792[14] | | | |

NOTES:

1. Assumed equivalent to a conveyor.
2. Arbitrary value.
3. Nominal value x 2 for severe service (acid fumes).
4. The acid regeneration plant vendor nominally installs 33-100 percent redundancy.
5. Nominal value x 2 for severe service (aqueous acid).
6. Nominal value x 2 for severe service (aqueous acid).
7. Nominal value x 2 for severe service (aqueous acid).
8. Nominal value x 2 for severe service (acid fumes).
9. Nominal value x 2. Power plant value considered unrealistically low.
10. Acid regeneration plant vendor indicates 20 year refractory life. Nominal value x 1/2 to allow for more severe conditions than in standard acid regeneration plant.
11. Plugging of solids discharge most common failure. Value for conveyors used.
12. Spray nozzle clogging most likely failure. Value of 1/2 that for a dry scrubber used, as sprayed solution is clean.
13. Nozzle plugging most likely failure. Taken as 1/4 the value for a dry scrubber to account for clean water, much larger nozzles.
14. Availability of full plant capacity. Due to parallel operation of the dissolution process, the availability of 2/3 capacity will be somewhat higher.

TABLE L-6. ACID ROASTER SYSTEM, 5000 LB/HR

| Equipment Item | No. in System | Unavailability, hr/hrx10$^6$ | |
|---|---|---|---|
| | | Equipment Item | System |
| **Dissolution Chamber** | | | |
| Munitions loader | 15 | 360[1] | 5400 |
| Dissolution chamber | 15 | 100[2] | 1500 |
| Chamber closure | 15 | 152 | 2280 |
| Vent fan | 1 | 96[3] | 96 |
| Dissolution pumps | 6[4] | 40[5] | 240 |
| Acid cooler | 3 | 160[6] | 480 |
| Valves and piping | 6 | 50[7] | 300 |
| Duct | 15 | 16[8] | 240 |
| Chamber unloader | 15 | 360[1] | 5400 |
| Instrumentation | 90 | 46 | 4140 |
| **Roaster/Afterburner** | | | |
| Burner | 2 | 594 | 1188 |
| Combustion air blower | 2 | 48 | 96 |
| Fuel supply | 2 | 14[9] | 28 |
| Spray nozzles | 1 set | 2381 | 2381 |
| Refractory | 1 | 1141[10] | 1141 |
| Solids discharge | 1 | 360 | 360 |
| Roaster feed pumps | 2 | 40[5] | 80 |
| Cyclone | 1 | 360[11] | 360 |
| Oxide blower | 1 | 48 | 48 |
| Duct | 1 | 16[8] | 16 |
| Instrumentation | 8 | 46 | 368 |
| **Acid Regeneration** | | | |
| Cyclone gas cooler | 20 | 160[6] | 3200 |
| Isothermal absorber | 2 | 1190[12] | 2381 |
| Bottoms pump | 2 | 40[5] | 80 |
| Cooler | 1 | 160[6] | 160 |
| Acid makeup pump | 1 | 40[5] | 40 |
| Adiabatic absorber | 1 | 1190[12] | 1190 |
| Cooler | 1 | 160[6] | 160 |
| Valves and piping | 4 | 50[7] | 200 |
| Duct | 1 | 16[8] | 16 |
| Instrumentation | 19 | 46 | 374 |
| **Pollution Control** | | | |
| Dry scrubber preheater | 1 | 80 | 80 |
| Dry scrubber | 1 | 2381 | 2381 |
| Discharge conveyor | 1 | 360 | 360 |
| Chemical feeder | 1 | 360 | 360 |
| Pump | 2 | 40[12] | 80 |
| Duct | 1 | 8 | 8 |
| Bag house | 1 | 274 | 274 |
| Discharge converyor | 1 | 360 | 360 |
| Duct, stack | 1 | 8 | 8 |
| ID fan | 2 | 48 | 96 |
| Instrumentation | 6 | 46 | 276 |

TABLE L-6. (continued)

| Equipment Item | No. in System | Unavailability, hr/hrx10$^{5}$ Equipment Item | System |
|---|---|---|---|
| **General** | | | |
| Switch Gear | 1 | 12 | 12 |
| Hydraulic power | 5 | 220 | 1100 |
| Central control | 1 | 746 | 746 |
| Cooling tower | 1 | 595[13] | 595 |
| Cooling water pump | 1 | 20 | 20 |
| Room, doors | 6 | 200 | 1200 |
| Total System Unavailability | | | 42,499x10$^{-5}$ |
| Total System Availability = 1-0.424 = 0.576[14] | | | |



NOTES:

1. Assumed equivalent to a conveyor.
2. Arbitrary value.
3. Nominal value x 2 for severe service (acid fumes).
4. The acid regeneration plant vendor normally installs 33-100 percent redundancy.
5. Nominal value x 2 for severe service (aqueous acid).
6. Nominal value x 2 for severe service (aqueous acid).
7. Nominal value x 2 for severe service (aqueous acid).
8. Nominal value x 2 for severe service (acid fumes).
9. Nominal value x 2. Power plant value considered unrealistically low.
10. Acid regeneration plant vendor indicates 20-year refractory life. Nominal value x 1/2 to allow for more severe conditions than in standard acid regeneration plant.
11. Plugging of solids discharge most common failure. Value for conveyors used.
12. Spray nozzle clogging most likely failure. Value of 1/2 that for a dry scrubber used, as sprayed solution is clean.
13. Nozzle plugging most likely failure. Taken as 1/4 the value for a dry scrubber to account for clean water, much larger nozzles.
14. Availability of full plant capacity. Due to parallel operation of the dissolution process, the availability of part capacity will be substantially higher.

TABLE L-7. VACUUM FURNACE - RAM FACTORS

| Equipment Item | No. in System | Unavailability, hr/hr x $10^5$ Equipment Item | System |
|---|---|---|---|
| **Vacuum Furnace** | | | |
| Locks | 4 | 250 | 1000 |
| Furnace Shell | 1 | 100 | 100 |
| Furnace Heater | 1 | 100 | 100 |
| Furnace Power Supply | 1 | 100 | 100 |
| Refractory | 1 | 1141 | 1141 |
| P, T Instrumentation | 8 | 46 | 368 |
| Duct | 1 | 8 | 8 |
| Feed Conveyor | 1 | 360 | 360 |
| Discharge Conveyor | 1 | 360 | 360 |
| Furnace Conveyor | 1 | 720[1] | 720 |
| **Vacuum Pump** | | | |
| Vacuum Pump | 2 | 120[5] | 240 |
| Separator | 2 | 360 | 720 |
| Pipes, Valves | 1 | 50[2] | 50 |
| Chemical Feeder | 1 | 360 | 360 |
| Pump | 1 | 240[3] | 240 |
| P, T level, Flow Instrumentation | 16 | 46 | 736 |
| **Afterburner** | | | |
| Afterburner Refractory | 1 | 1141 | 1141 |
| Combustion Air Blower | 1 | 48 | 48 |
| Burner | 1 | 594 | 594 |
| Fuel Supply | 1 | 14[4] | 14 |
| P, T Instrumentation | 6 | 46 | 276 |
| Duct, stack | 1 | 8 | 8 |
| **Dryer** | | | |
| Dryer | 1 | 2381 | 2381 |
| Burner | 1 | 794 | 794 |
| Combustion Air Blower | 1 | 48 | 48 |
| Fuel Supply | 1 | 14[4] | 14 |
| Pipe, Valves | 1 | 50[4] | 50 |
| P, T, Flow Instrumentation | 5 | 66 | 330 |
| Duct, Stack | 1 | 8 | 8 |
| **General** | | | |
| Switch Gear | 1 | 12 | 12 |
| Hydraulic Power | 1 | 220 | 220 |
| Central Control | 1 | 746 | 746 |
| Room, Doors | - | 200 | 200 |
| Total System Unavailability | | | $13,487 \times 10^{-5}$ |
| Total System Availability = 1-.135 = 0.865 | | | |

NOTES:

1. Nominal value x 2 for severe service - conveyor
2. Nominal value x 2 for severe service - pipe
3. Nominal value x 2 for severe service - pump
4. Nominal value x 2. Nominal value for power plants considered unrealistically low.
5. Severe service because of gas composition.

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